INTRODUCTION TO GEOLOGY

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GENERAL GEOLOGY

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PREFACE

THIS little book on elementary Geology originated out of a first-year course of lectures delivered, in ever changing form, at Glasgow University during the years 1930 to 1937. The palaeontological chapters, V and XLIII to LVII, have been written by Dr. John Weir, the remainder by myself. The illustrations, apart from those listed under the heading *Acknowledgments*, have been drawn by Dr. W. J. McCallien.

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Glasgow University has accepted the copyright, and proposes to devote any profit towards field expenses incurred during research by members of the University geological staff. This is most useless book for the stud

E. B. BAILEY

20th September, 1938.

ACKNOWLEDGMENTS

TWO-THIRDS of the figures have been specially drawn, though in many cases as adaptations or copies of published illustrations. Among the chief sources have been photographs in the collections of the Geological Survey and British Association. Reference is made to originals in explanations of individual figures, and the authors desire here gratefully to acknowledge their deep indebtedness. The figures numbered below have been reproduced directly from published illustrations with kind permission of the authorities concerned.

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INTRODUCTION TO GEOLOGICAL PHENOMENA

CHAPTER I

REPRESENTATIVE DISCOVERIES

The word Geology is derived from the Greek *ge*, the earth, and *logos*, science. Geology is the Science of the Earth, and is especially concerned with the history of the Earth in past ages. If the importance of a science is measured by the number of unexpected and impressive discoveries which it has made, then Geology may be given a very honourable place. Let us pass some of these discoveries in review ; they will constantly reappear as we proceed with the course.

Interchange of land and sea.—In innumerable localities marine fossils can be found embedded in solid rocks that appear at the surface of the dry land, even at great heights above sea level. The explanation of these fossils was debated for centuries, and it was held by some in the sixteenth and seventeenth centuries that they were mere sports of Nature, mimicking true shells, corals, etc. Sports do actually occur, and every year are brought in by beginners who have been deceived by some superficial resemblance ; but for a long time now the reality of vast multitudes of fossils has been accepted, because the fossils have been made a subject of careful examination by trained biologists, who find in them just the same sort of structures, in detail, as occur in living organisms. After we have satisfied ourselves that a particular set of fossils is genuine, we still have many questions to settle. For instance, if our fossils are shells or corals, can we decide whether the animals of which they are the remains lived on land or in water and, if in water, was the water fresh or salt? This is again a question for the experienced biologist. Each fossil is compared with its living relatives so as to form an idea of its probable habits. Thus if the fossil is a shell of the coiled univalve type that we find in garden snails, or sea whelks, we have to be careful in our judgement, for obviously such snail-like creatures live to-day both on land and in water, and more minute comparisons are required before we can decide the habitat of our fossil.

On the other hand, if the fossil is a shell of the bivalve type that we find in oysters and cockles, we are safe in saying that it lived in water, not on land ; but we must study it carefully before we can say whether the water was fresh or salt, for, whereas oysters live in the sea, there are many bivalved creatures called freshwater mussels that live in our rivers.

Lastly if the fossil is a coral we can give an immediate answer. To-day all corals live in the sea, and the study of Geology consistently confirms the deduction that all corals in the past have also lived in the sea. This statement means that whenever we find a fossil coral its associates are of types which we should independently interpret as marine.

In an introduction such as this it is only possible to outline an argument, not to present convincing detail. Let us accept provisionally that geologists, with the help of biologists, have been able to decide which fossils are of land, which of fresh water, and which of marine origin, and that very many of the fossils that occur inland, even at great altitudes, are marine.

The next question, which was debated in the early days of our science, was whether the marine fossils found on land had lived where they are now situated, say in the middle of Europe, or whether they had actually lived on the sea beds of the present-day oceans, such as the Atlantic, and had then been transported into their present remarkable position. For instance, Noah's deluge was often in the past called to the aid of Geology, and was held responsible for washing numberless marine creatures far inland from the bed of the sea. This suggestion has been completely abandoned as a general explanation. Here is one of a multitude of arguments. Many of the fossils which we find are quite manifestly in the position of growth. Thus there are well-known layers of rock, extending horizontally for twenty miles or more, that consist of corals joined together. Such a layer is a fossil coral reef (Fig. 10). No one who looks at it could imagine that it had been swept into its present inland position by the help of a deluge.

Accordingly all geologists admit as abundantly proved that land and sea have interchanged. At certain periods in the geological past the British Isles have been completely, or almost completely, covered by the sea. To mention one item of evidence, Snowdon, the highest mountain in Wales, has marine fossils embedded in the rocks that form its very summit.

We shall deal later in some detail with the problem of how fossils have so often come to be entombed in solid rock. It is enough at present to remark that a fossil in a sandstone is the geological equivalent of a modern shell buried in sand.

BRITISH VOLCANOES.—A great many people are aware that there are extinct volcanoes in Britain. Yet no member of the human race has seen a British volcano in eruption. When the discovery was first announced that British volcanoes exist, though totally extinct, it was received with scepticism ; but to-day all doubt has disappeared. The argument may be stated under three heads :

(1) Many British rocks resemble the products of active volcanoes so closely that there can be no doubt that they are volcanic too. When this was first established, geologists had nothing more powerful to help their vision than a pocket lens. Later, methods were developed for the microscopic

examination of thin sections of rocks (Chapter XXVII), and the agreement of character was found to hold down to minute detail. The rocks of the main part of Snowdon, of Borrowdale, of the Campsie Fells and Kilpatrick Hills, of Mull and Antrim, provide examples.

(2) It is possible to reproduce the characters of these rocks in the laboratory by cooling melts of the proper chemical composition, but not in any other known fashion.

(3) Similar rocks are often found veining and disturbing associated rocks in the field, in a manner that shows they must have been injected in a liquid condition (Fig. 107).

Here it is necessary to utter a warning. One must not jump to conclusions. In Science one must not trust to a single line of argument. It is often thought by intelligent people, who happen to have had no scientific training, that some of the conical mountains of Scotland are old volcanic cones. Their shape agrees with this interpretation, except for the absence of a crater at the top. Such an agreement is always worth following up. On examination, however, it is found that there is no volcanic cone in Scotland. Schiehallion, for instance, the famous mountain against which scientists ‘ weighed the earth ’, consists of non-volcanic rocks. As for our real volcanoes, such as occur in plenty in the Campsie Fells, they are all too old to retain their original shapes. They have crumbled away like ancient castles. We can recognise them by their substance, not by their form. They are in ruins.

British ice-sheet.—The glaciers of Britain were as unexpected as the volcanoes, and yet have been demonstrated equally beyond doubt. One indication is afforded by the scratches, which still remain on many rock surfaces (Fig. 1), scratches exactly similar to those seen on rocks from which Swiss glaciers have melted within human memory. Another bit of evidence is the occurrence of recognisable stones, often themselves scratched, carried long distances, even hundreds of miles. Thus Highland stones have been carried in great numbers across Lowland Scotland into England, in a manner that cannot be attributed to rivers or to any other agent of transport except glaciers. Additional evidence is furnished by fossils, such as the bones of mammoth (Fig. 323) and woolly rhinoceros (Fig. 15) and the remains of arctic shell-fish and arctic plants, which lived alongside the ice-sheets and were manifestly suited to an arctic climate.

Scenery.—One of the greatest services that Geology has rendered to mankind is in the interpretation of scenery. Geology teaches us that, in the main, scenery is a work of sculpture, technically spoken of as erosion, from a Latin word meaning *gnawing away*. There are many agents of erosion, and chief among them are the streams and rivers. The landscape of Britain is essentially the same as the channelled surface of a sandy foreshore attacked by rivulets in the short interval between successive tides—only the scale is vastly different. The valleys are the channels cut by erosion. The mountains are what remains between, waiting in turn for demolition.

This great lesson was not easy to learn, but it has been established now for many years. One fact in support may be cited. If we look around us, and see a crag or mountain range, we always find on examination that it consists of unusually hard rock. Examples are of all sizes from Arthur's Seat to the English Lake District or the Highlands of Scotland. They stand up above the general surface because their material has from its hardness resisted the attack of erosion more successfully than adjacent softer rocks. They have not been preferentially upheaved by some subterranean force.

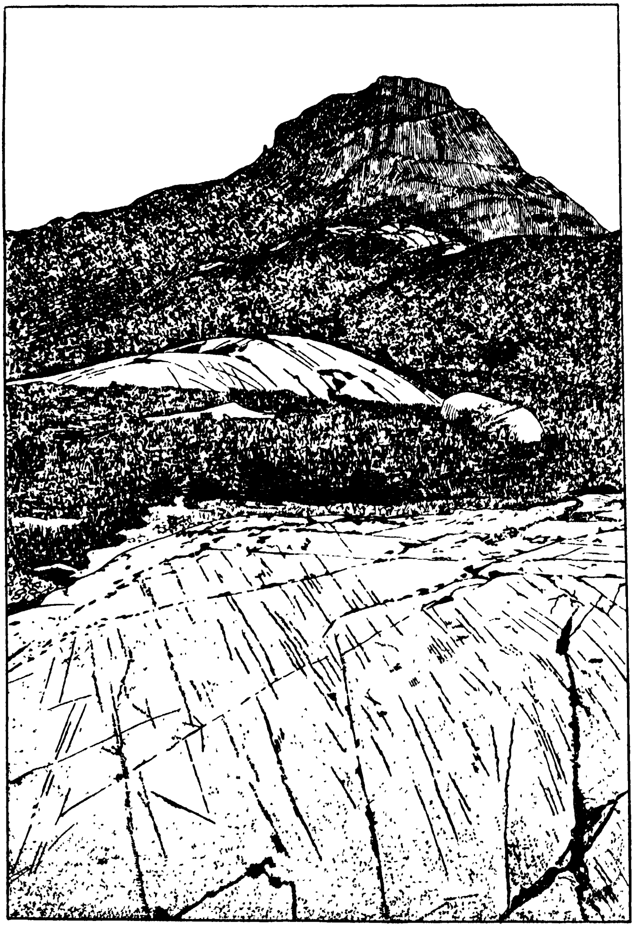

FIG. 1. Striated rock surfaces near Glen Roy.
(Geol. Surv. photo.)

GEOLOGICAL TIME.—Once geologists realised that scenery is a product of erosion, they made another unexpected discovery : the earth must be almost incredibly old. Roman walls and Roman roads can still be traced across the face of our country. The general surface, therefore, has scarcely been modified during the past 1500 years. Either we must doubt the erosion origin of scenery, or we must allow that the carving of Britain has taken many millions of years.

At one time Lord Kelvin thought the claims of geologists on the bank of time were extravagant. Now, however, that radium has been discovered and its heat-producing disintegrations recognised, physicists have come to see that geologists were correct, and have given us invaluable assistance in actually numbering the millions of years that have passed in the history of the globe.

EVOLUTION OF LIFE.—One of the most important discoveries of Science is summarised under the heading evolution. Life has developed from simple forms to complex. Evolution could scarcely be doubted on the evidence directly supplied by Zoology and Botany ; but let us never forget that the only actual record of the course followed by evolution is that which is preserved, however imperfectly, in the rocks. It belongs to Geology. The fossils of the latest rocks differ little from the living creatures of to-day. As we go back in the geological record we find greater and greater divergences of type. The older fossils in some cases can be shown to be ancestral to the modern forms. In other cases they have died without leaving descendants.

MOUNTAIN STRUCTURE.—Let us mention one further discovery. Sometimes we find rocks that have been driven many miles horizontally, in great slices, over their fellows. The picture one gets is much the same as that presented by an arctic sea, where ice floes have crashed into, and ridden over, one another.

One of the main questions at present discussed by geologists is : Do continents drift? To this no definite answer can be given, but it will be possible in the sequel to indicate the sort of evidence that suggests the possibility that, for instance, South Africa and South America once lay side by side (Fig. 307). Perhaps the matter may be settled by measurement, for a succession of longitude observations taken at a particular site in Greenland makes it appear possible that Greenland is nowadays drifting at an appreciable rate towards America.

CHAPTER II

ROCKS (MAINLY SEDIMENTS)

GEOLOGY is chiefly concerned with rocks, for these furnish it with the material of most of its story. To begin with, therefore, it is well to know what is meant by the word rock. As in the case of many other words there are differences of meaning, which can usually be understood only by the context. Thus rock is often defined in textbooks in a very inclusive sense as : Any natural dead solid matter which occurs in bulk.

According to this definition most of what we know on earth, except the air and water, the plants and animals, consists of rocks. The loose sand of the seashore is rock, even though it may be quite unconsolidated and largely or wholly made of shell fragments. Peat too is rock in this sense. But individual shells, or bones, are not rock ; nor is an individual crystal, because it does not occur in bulk.

The word rock, however, is also used in a more restricted sense to mean consolidated natural matter which occurs in bulk.

This more restricted use excludes soft sands and clays and peats. It is in keeping with everyday non-geological practice, and has its definite place in Geology.

There are many different kinds of rocks. We shall consider them under four headings : Sedimentary ; Igneous ; Veinstones ; Metamorphic.

SEDIMENT

In Geology a sediment, or sedimentary rock, is defined as any non-volcanic rock deposited on the solid surface of the earth, either under air or under water.

Such sediments may be further classified as mechanical, organic, and chemical.

MECHANICAL SEDIMENTS.—The mechanical sediments are made up of fragments, large or small ; they are also called clastic sediments, from a Greek root meaning *broken*. The fragments of which they are composed are derived from pre-existent rocks, and this has given rise to still another common name for the group, namely detrital sediments, from a Latin root meaning *rubbed away*.

The main divisions of the mechanical sediments are as follows :

Unconsolidated	*Consolidated*
Gravel	Conglomerate
Sand	Sandstone
Mud, clay, silt	Mudstone, shale

The origin of the coarser mechanical sediments presents no difficulty. In every feature, apart from consolidation, a conglomerate is obviously a gravel, and a sandstone obviously a sand. The interpretation of mudstones and shales as consolidated muds is more difficult, since the fragments that go to make a mud are frequently so small that they cannot be individualised even with a microscope. The evidence is as follows :

FIG. 2. Mudstone crowded with fossil shells of Liassic age.

(1) Shales and mudstones occur interlayered among sandstones, just as mud is interlayered among sand.

(2) They often contain fossils recalling the shells and plant-remains that may commonly be found in mud (Fig. 2).

(3) On chemical analysis they agree with mud, just as a sandstone on chemical analysis agrees with sand.

Having settled the origin of these various types of sediment, the next question is the cause of consolidation or hardening.

There are various processes at work, either singly or in combination : pressure, heat, cement.

Pressure.—The consolidation of rocks, which consisted originally of soft deformable material, such as clay or peat, is largely due to pressure. The pressure is generally caused by the weight of superincumbent material. We shall learn presently that it is a commonplace for a layer of sediment to be covered up by layer after layer of other sediment, until a mile or more has accumulated upon its top. This exercises enormous pressure. The particles are brought into close contact and forced to fit together. It is quite easy, for instance, to compress peat artificially and obtain from it a hard substance resembling coal. The consolidation of mud to mudstone, or shale, is mainly due to pressure.

HEAT.—When rocks are buried to great depths their temperature rises and this helps in consolidation. There is another way in which buried sediments can become heated. We have already spoken of volcanoes, both ancient and modern. At volcanoes molten material is coming up from below to the surface of the earth. It brings its high temperature with it and heats the rocks it meets underground. Rocks, heated in this fashion, and later exposed to observation by erosion, are found to be intensely hard. Such a hard baked rock is called hornfels, a German word, in which *horn* means the same as in English, while *fels* means rock. A hornfels is so called because many baked rocks, when broken, have a smooth and rather shiny surface like polished horn. The hardening of rocks by heat is a practice that man adopts when he bakes clay into brick.

CEMENT.—When man wishes to build a house of bricks he mortars the bricks together with a calcareous cement which sets and binds. Similarly much of the consolidation of rocks is due to cement. There are three main cements :

Calcareous - - - -	$CaCO_3$
Ferruginous - - -	Fe_2O_3
Siliceous - - - -	SiO_2

Calcareous sandstones are white or grey. Their cement is calcium carbonate, the important ingredient of human mortar. They are easily shaped, but do not stand exposure to weather, especially to the acid atmosphere of a town. The calcareous cement or matrix is dissolved by acid, and the sandstone returns to sand, an unfortunate condition for the owner of a house built of such material.

Ferruginous sandstones are red, and are held together by iron rust. Almost all the common mineral colours of nature are due to iron in some form or another. One often finds sand lying about an old rusty anchor cemented to a ferruginous sandstone.

Other sandstones are bound by siliceous cement. They are pale in colour and may be very hard.

ORGANIC SEDIMENTS.—Organic sediments arise through the life processes of organisms. In composition they are mostly calcareous, but there are also important examples which are siliceous or carbonaceous.

The main groups may be listed as follows :

Unconsolidated	*Consolidated*	*Approximate Composition*
Shells	Limestone	$CaCO_3$
Radiolarian Ooze	Radiolarian Chert	SiO_2
Peat, etc.	Coal	C

Most limestones are in part made of the remains, large or small, of shells, corals, etc. Solution, followed by redeposition of some of the calcium carbonate, furnishes a cement, and limestones consolidate rapidly.

Radiolaria are microscopic marine organisms with siliceous skeletons (Fig. 118). The consolidated chert has a siliceous cement.

Coal, the chief carbonaceous sediment, results from the remains of plants. Peat is unconsolidated coal. In our climate peat is accumulating in bogs with few or no trees ; under tropical conditions it forms in mangrove swamps, etc. Most of our coal seams were forest growths, to begin with, rather than peat mosses.

FIG. 3. Bedding and jointing in Carboniferous sandstone, Muckross Head, Donegal. (J. R. Welch photo.)

CHEMICAL SEDIMENTS.—Chemical sediments are precipitates from solution with little or no help from organisms. Some limestones are chemical precipitates, but the most characteristic rocks of this class, if we leave ice out of consideration, are : anhydrite, $CaSO_4$; gypsum, $CaSO_4 . 2H_2O$; and rock salt, NaCl. Deposits of these minerals are only forming to-day in enclosed or semi-enclosed bodies of water, like the Great Salt Lake or the Dead Sea, which are evaporating under desert conditions.

Bedding.—Sediments, whether they form on the land, or in a lake, or in the sea, are deposited in layers. These layers are spoken of by geologists as beds, strata, or seams ; or, if they are very thin, laminae.

Fig. 4. Current bedding in Permian sandstone, Brodick, Arran. (Geol. Surv. photo.)

It is a common and quite unimportant mistake to think that strata is singular ; the singular is stratum, strata is the plural.

The word bed, stratum, or lamina is applied to a layer of any kind of sediment. The word seam is usually restricted to a bed of valuable material, such as coal.

Bedding or stratification is so characteristically developed among sedimentary rocks that these are often spoken of as the stratified rocks.

Bedding may be regular, in which case the beds have parallel plain tops and bottoms (Fig. 3).

Or it may be irregular, in which case the surfaces of successive beds are curved or meet one another at an angle.

Irregular bedding is called false bedding, because it may give a wrong impression as to the order of superposition of adjacent beds ; but this is a matter we have not yet reached. False bedding is classified according to origin and nature as follows :

- False Bedding
  - Current
    - Tip or Cross
    - Ripple
  - Slip

In current bedding the irregularities of the bedding are original, they are due to the currents which deposited the material. In the variety known as tip, or cross, bedding, the current builds out a succession of tilted laminae (Figs. 4, 310). It is very characteristic of deltaic accumulation. In the ripple mark type of bedding a surface is produced with a succession of little ridges and furrows. It is very often seen on a seashore or in sand dunes, and is produced by currents, either of water or wind.

In slip bedding the irregularity is due to slipping (Fig. 5). If a set of soft clays accumulate on a fairly steep slope, some time or another they are apt to slip down and crumple as they go, especially if shaken by an earthquake.

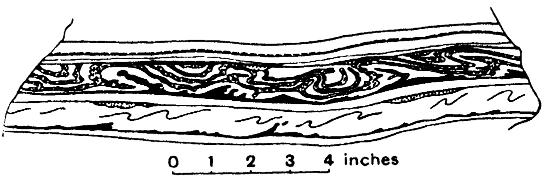

Fig. 5. Slip bedding in Ordovician sediments near Girvan. (After S. M. K. Henderson.)

Even regular bedding is not all of one type. If sediment of varied degrees of coarseness, such as a mixture of sand and clay, settles to the bottom through still water, its material tends to separate as it falls, for the coarser sand reaches the bottom earlier than the finer clay. Thus in some deposits we find a succession of beds, in which each bed has a relatively coarse base and a relatively fine top. Bedding of this type is said to be graded (Figs. 6, 7).

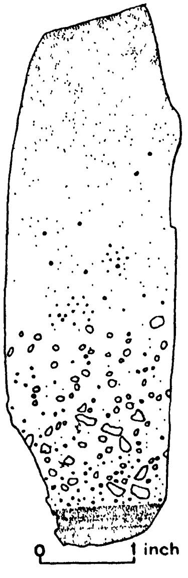

Fig. 6. Graded bedding in Precambrian grit, Inishowen, Donegal.

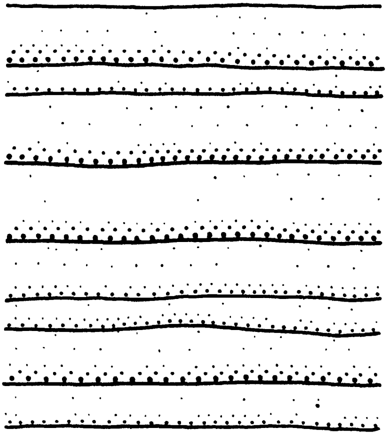

Fig. 7. Succession of graded beds.

Of late, particular attention has been paid to the characteristics of current, slip and graded bedding, and from this very simple source altogether unexpected geological facts have been deduced (Fig. 279); but we must know more about the subject as a whole to appreciate their true worth.

CHAPTER III

ROCKS (*concluded*)

IGNEOUS ROCKS

THE second great class of rocks is called igneous from the Latin *ignis*, a fire.

Igneous rocks may be defined as rocks which have consolidated from fusion or been produced by hot explosions.

They are familiar to all of us, at least by report, in lavas.

After a lava has consolidated, it may still retain recognisable evidences of its previous fluidity. Here, for instance, in Fig. 8, a man is seen prodding his walking stick into the still viscid surface of a very recent flow somewhere in Africa. The mark will continue. The same point is illustrated by pieces of lava, brought home by tourists from Vesuvius, and holding pennies that cannot be dislodged.

FIG. 8. Cooling lava, still soft, Albert National Park, Central Africa. (After H. Hackers, *Geog. Mag.*, 1937.)

Again, many specimens of modern consolidated lava are full of round holes blown up by steam. Steam escapes from solution in molten rock material when the latter reaches the surface, just as gas escapes from solution in soda water when the latter issues from a syphon. Subsequent consolidation of the lava preserves the shape of any of the bubbles that have not already burst. Thus the presence of bubbles in a solid rock tells us clearly that the rock was once liquid.

Bubbles in a lava are called vesicles, meaning little vessels ; often such vesicles later become filled with minerals deposited by percolating waters. The infillings are then called amygdales, because they resemble almonds in appearance, and *amygdalon* is the Greek for almond. Most agates, for instance, are amygdales. Britain has many vesicular and amygdaloidal rocks that are unquestionably lavas.

Some modern lavas after they solidify are in large part made of glass. The presence of similar glass in ancient lavas is another proof of the former molten condition of these rocks. Glass, at any rate of the chemical composition met with in lava, can only arise through the cooling of a melt. The glass of our windows and bottles has been made by cooling artificial melts.

Many lavas, both modern and ancient, contain abundant crystals, which have grown in the lava instead of, as in sediments, being introduced as fragments. This again is a suggestion of former fluidity ; but it is a matter that requires more discussion than is necessary in the case of glass. The commonest type of lava in the world, basalt, is generally crystalline rather than glassy.

Any natural molten material is called by geologists magma. Magma may occur underground or at the surface of the earth. In the former position it is spoken of as intrusive magma, and in the latter position it is called extrusive magma or molten lava. Magma ceases to be magma when it consolidates to rock. Intrusive magma consolidates to a solid intrusion ; extrusive magma to a solid lava.

It will be noticed that the word lava can be applied to either molten or solid material. Some people also use lava to cover magma in any position ; but this is an unfortunate practice for it tends to lose sight of the difference between intrusions and lavas, which for many geological purposes is an extremely important matter.

It is easy to examine intrusions, as well as lavas, in many parts of the north and west of Britain. Let us take as an example a well-known intrusion occurring at the famous Fossil Grove in Glasgow. It is of a type called dolerite. It has cooled underground, and this has led to slower cooling and more crystalline texture than is common in a lava. Thus it contains no glass except at its margin, where it came in contact with cold sedimentary rocks and got suddenly chilled. Soon it heated up the neighbouring sediments, and, after that, its own interior cooling became a very slow process. The original liquidity of the dolerite is best shown by the way it has disturbed the sediments into which it has been intruded, and by the way it has penetrated them as narrow veins.

Granite is another intrusive rock-type. Its igneous nature was deduced by a Scottish geologist called James Hutton from an examination of its crystalline texture in hand specimens. He then went to Glen Tilt in 1785 to see how granite behaves in the field, and to his delight found that it had penetrated neighbouring rocks in narrow veins, which shows that it must have been liquid when it came into position. This constitutes one of the historic triumphs of geological investigation.

Fig. 9. Dyke, Corriegills shore, Arran. The dyke owing to its jointing has been preferentially washed out by the waves. Note hardened sandstone at contact.

Intrusions, even where they consist of identical material, such as dolerite, may differ greatly in shape. There are two very common forms of intrusion which it is convenient to define at this early stage.

A dyke is an approximately vertical intrusion with parallel sides. Most dykes are of very moderate width, and so resemble walls in shape, which accounts for the name that has been given to them (Fig. 9).

A sill is an intrusion which approximately follows the bedding. The dolerite at the Fossil Grove occurs as a big sill with minor sills associated. The dolerite at Hound Point on the Firth of Forth is another example. Fig. 107 illustrates very clearly how its base locally transgresses the bedding of associated sediments.

VEINSTONES

The veinstones are very unimportant from the point of view of bulk, but very important from the point of view of the value of their materials. They may be defined as underground deposits from solution.

Where the solution has been cold, the vein may approximate to a chemical sediment, except that it has formed underground ; where the solution has been hot, it has often been the emanation of a magma, and the distinction between veinstones and igneous rocks becomes arbitrary.

The metalliferous sulphides and other valuable ore-minerals mostly come from veinstones (Chapter XXII).

METAMORPHIC ROCKS

Where rocks have undergone an exceptional amount of change, they are said to have been metamorphosed. The common structural and mineralogical changes involved in mere consolidation or weathering do not qualify a rock for the title. At this stage it is enough to state that shale may be metamorphosed into slate as a result of pressure, or more complex stress, and into mica-schist by co-operation of stress and heat. Igneous rocks can also be metamorphosed. Thus basalt and dolerite are changed to hornblende-schist, while granite may be altered to a variety of gneiss (Chapter XXIV).

GEOLOGICAL DEDUCTIONS

Let us turn aside to notice the sort of information which follows from a very elementary study of rocks. For instance :

(1) A shale full of marine fossils high above sea level indicates either upheaval of a part of the sea bottom or a withdrawal of the sea. In almost all cases it means the former, but we require more evidence than is given above.

(2) Extinct fossils tell us that the containing deposit accumulated so long ago that much subsequent change has occurred in the life of the world (Fig. 2).

(3) A fossil coral reef in Britain shows that the climate of our country was once much hotter than to-day, because coral reefs are now restricted to warm seas, mostly within the tropics (Fig. 10).

(4) Deposits of rock salt and gypsum in Cheshire show that the climate was once that of a desert.

(5) Fossil rootlets piercing the rock beneath a coal seam (Fig. 11) show that the plants that have formed the coal grew in the place where we now see the coal. The root-bed is an essential part of the evidence. Plants can float, and are often drifted by water currents far away from their place of growth before being deposited—for instance Siberian trees are carried in

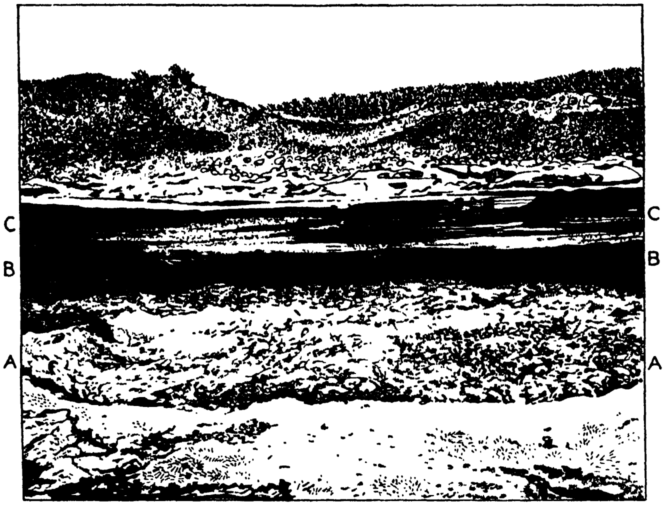

Fig. 10. Coral limestone, A, under coal, B, under marine shale, C, under modern shingle and blown sand, East Lothian. (Geol. Surv. photo.)

great numbers to Spitsbergen ; but a coal resting upon its root-bed, or seat-earth, has evidently grown where we find it. This is very important, for the

Fig. 11. Fossil root penetrating coral limestone, A of Fig. 10. (Geol. Surv. photo.)

plants of such a coal give an indication of the climate of the place where they are found ; whereas the Siberian trees just mentioned give no indication of the climate of Spitsbergen to which they have wandered.

We have in these few instances noted that Britain formerly enjoyed much warmer climates than at the present day. This supports the view that the continents are drifting and that Britain long ago was much farther south than it is to-day.

(6) A succession of basalt sheets with vesicular tops at the Giant's Causeway shows that Antrim has had its volcanoes.

(7) Soon after entering the Highlands at Luss or Aberfoyle we meet with great slate quarries. We begin to understand what is meant by those who tell us that most of the rocks of the Highlands are metamorphic.

(8) We climb from Glen Nevis up Ben Nevis and note that we are walking on granite. We wonder why, if granite formed from fluid magma, this latter did not flow down and block the glen (Fig. 91). Suddenly we realise that erosion has cut out the glen long after the consolidation of the granite.

CHAPTER IV

TECTONICS AND MAPS

EARTH MOVEMENT.—At the present time the earth's crust is very stable in the British Isles. There is occasionally a slight tremor, or earthquake, as it is called, but within human record British earthquakes have all been very tame affairs. It is far different in many other regions of the globe, for instance in the Mediterranean belt, including Italy, and in the Circum-Pacific belt, including New Zealand, Japan, Alaska and California (Fig. 110).

Earthquakes are vibrations, and are now recognised as a transitory symptom of earth movements that cause permanent displacement of the earth's surface. The largest single displacement on land that has been measured in connection with a modern earthquake was an elevation of part of the Alaskan coast by as much as 47 feet in 1899.

Displacements, such as occur occasionally to-day, have also happened in the past in many parts of the world, as is clearly to be read in the geological record. Excavations show that, since Roman times, considerable subsidence has occurred in London, for they have uncovered land surfaces of the period well below present-day sea level. The movement has probably been affected in very small stages. In Scotland little or no change has occurred since the Roman invasion ; but at a somewhat earlier date, still within human occupation, there was marked elevation. The coast of Scotland is bordered by a low terrace, capped with shingle and backed by a cliff containing obvious sea caves, now high and dry. This terrace is called a raised beach, because from its nature it is evidently a sea beach, though it stands well above high water mark (Fig. 325). Again the old question may be asked : has the land risen or the sea fallen? We may answer in this case that the land has risen, because the beach is not everywhere at one and the same elevation above the modern shore line ; in fact, it does not extend far into England, and is absent even from the Outer Hebrides and the Orkneys and Shetlands. The date at which the upheaval occurred can be roughly fixed, for the canoes of our stone-age predecessors have on rare occasions been found in the deposits of the beach.

Similarly in Sweden it is easy to prove that there has been elevation of mid Sweden during human times, and that it has been accompanied by depression of southern Sweden.

Examples might be multiplied. Clearly the earth's crust moves, rises, falls, tilts and bends ; and, according to many observations made in connection with modern earthquakes, it breaks.

Movements of the earth's crust are partially recorded in their effects upon the bedding of sedimentary rocks. Most, though by no means all, slopes on the bottom of the sea are very gentle indeed. Thus layers or beds of sediment, as a rule, accumulate almost horizontally. Subsequent tilting of the earth's crust gives the beds an inclination. In Britain, which despite its present calm has had a very troubled past, the majority of bedded rocks have a decided inclination. Some even are vertical or overturned. This condition does not hold everywhere. For instance, in the interior of Russia, or in the interior of North America, there are great areas, where even very old rocks, though upheaved, remain almost flat.

The inclination of a bed is called dip, and can be measured in the field with a simple instrument called a clinometer. The dip at any particular locality is indicated on a geological map by an arrow pointing in the direction of greatest inclination. This direction is taken with a compass, and it must be remembered that a compass needle very rarely points to the true north. The divergence, or declination as it is called, varies both with locality and date. At London, for instance, the compass pointed 11° E. of N. in 1580, true N. in 1652, 24° W. of N. (an extreme value) in 1810, and 13° W. of N. in 1935. The local value for some particular date is often indicated on the margin of a map, along with an estimate of the rate of change. Suppose magnetic north lies 15° W. of N., we must, if we want the compass card correctly orientated, let the needle come to rest at the mark 15° W. of N.

Just as an inclined bed has one particular direction in which the inclination is greatest, so also it has another direction in which the inclination is zero. The direction of zero inclination, that is of horizontality, of a bed is called strike. It follows at once that strike is always at right angles to dip.

If a bed is horizontal in all directions it has no definite direction of dip, or strike. The map symbol for horizontality is an upright cross with equal arms.

If a bed has been so tilted as to become vertical its attitude is marked on the map with a longer line in the direction of strike, crossed by a shorter line at right angles.

The earth's crust is not tilted uniformly in one direction, otherwise it would presently reach upward to heaven and downward elsewhere. It is bent into arches and depressions. These structures are very clearly represented in the attitude of bedding. Any bend in bedding is called a fold.

An arch-fold, where beds dip outwards on either side from a central line, is called an anticline (Fig. 12).

A trough-fold, where beds dip inwards from either side towards a central line, is called a syncline (Fig. 25).

The central line is called the axis of the fold.

The definitions given above for anticline and syncline are replaced by more general definitions in Chapter XXIII.

Beds, including laminae, are the ultimate units of stratigraphy, and the presence of bedding planes is of the greatest service in helping us to unravel the structure of the earth's crust and the deformations which it has undergone. Geological structure is so important a subject that it has been given a special name, Tectonics, which is based on the same Greek word as appears in architecture. For detecting dip and strike and certain other elements of structure, beds are the most convenient units; but for many purposes they are inconveniently thin. This brings us to the next stage in our stratigraphical classification.

FIG. 12. Anticline in Coal Measures, Saundersfoot, Pembrokeshire. (Geol. Surv. photo.)

FORMATIONS.—A formation is a stratigraphical unit limited at top and bottom by bedding planes, and defined by some character chosen for convenience. Note that the definition of any particular formation is a matter of convenience. In very exceptional circumstances it may be convenient to take a single bed as constituting a formation. Much more often a great number of beds with some common characteristic are taken together and treated as a single formation, tens, hundreds or even thousands of feet thick. Again, since formations are units of convenience, one and the same succession of beds for some particular purpose may be grouped as a single formation, and for another purpose may be split up into two or more formations.

There are three main characters by which formations are defined: lithology, fossils and succession.

(1) Lithology means rock character from the Greek *lithos*, a stone, and

logos, science. Most of you have seen or heard of the white cliffs of England, which by the way reappear in Antrim. They are made of a distinctive white limestone called chalk, and it is an easy matter to understand that the Chalk Formation is a convenient stratigraphical unit defined by lithology.

(2) Fossils supply the subject matter of Palaeontology, which literally means the science of ancient life, based upon Greek words *palaeos*, ancient; *ontos*, being. When geologists came to study the Chalk Formation they found that the upper part contains a fossil sea urchin called *Micraster* (Fig. 318), which does not occur in the lower part. Thus it has been possible to establish the Upper Chalk Formation on palaeontological evidence.

(3) Succession is something that we shall understand more fully presently. For the moment suppose that in some district we find an easily definable formation, A, overlain by a heterogeneous assemblage, B, and this in turn by an easily definable formation, C; it may be convenient to call B a formation, and define it as containing all the beds that intervene between A and C.

EROSION OF FORMATIONS.—It is clear that deposit and erosion are necessary accompaniments. It would be impossible to continue for long depositing sediment on any one part of the earth's surface, unless some other part were suffering erosion to supply the requisite material.

It is also clear that erosion, if it is to continue, must be accompanied by elevation. Erosion is incessantly lowering those portions of the earth's surface that are exposed above sea level, so that it would in time remove all protuberances, were it not for compensatory upheavals, such as are recorded by elevated tracts of marine sediments.

Elevation of marine sediments, coupled with erosion, supplies ideal opportunities for study of geological formations, including that supremely important matter the order of succession of geological formations.

Let us consider a few very simple, and at the same time typical, examples.

Suppose a set of marine formations has been elevated, and that the sea has cut or eroded its way into the new land, thus producing a vertical cliff. Such a sea cliff furnishes what we call in geology a natural vertical section, where section means nothing more nor less than a cutting. In a cliff the order of succession of geological formations is self-evident: if at any particular place there are two formations in the cliff, the upper formation occupies the upper part of the cliff (Fig. 13).

The sea in making a cliff, also cuts a flat surface in the rocks at the foot of the cliff. A flat section does not give us any insight into the succession of formations, so long as these formations have themselves remained flat; but it does give us a great deal of information if it has been cut across inclined, that is dipping, formations. A moment's consideration shows that on a flat surface successively higher formations come to occupy the surface in the direction of dip (Fig. 13A).

Here one may introduce a technical word, outcrop. Where a formation comes to the surface it is said to outcrop or crop out, and the area in which it lies at the surface is called its outcrop. Usually superficial deposits, such as sea sand for instance, are left out of consideration in speaking of the outcrops of solid rocks. Thus one is quite correct in speaking of an outcrop of chalk, on such and such a beach, even where the actual surface is covered over by sea sand, so long as chalk is the first solid rock below the sand.

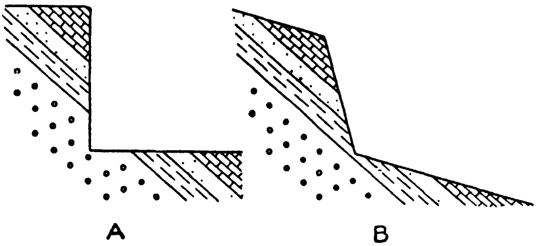

FIG. 13. Relation of outcrop to dip and slope.

If we want to say that a formation is to be seen naked at some particular locality we use the word exposure.

Let us now return to the flat section cut by the sea across dipping formations. If we make a geological map of such a flat, and colour each formation with a distinctive tint, we shall have bands of colour running across our map. A little consideration will show that on a horizontal surface the direction of outcrop of dipping strata corresponds with the direction of strike.

Let us proceed from the simple cases presented by a cliff and a flat to the slightly more complicated case of an upland country, cut into hills and valleys by rivers and other subaerial agents of erosion.

The first essential is to remember how ordinary geographical contours run in such a district. The contours make their way horizontally along the hill sides, and whenever they come to a valley, to maintain their horizontality, they bend upstream in the form of a V with the apex pointing upstream.

Where hills and valleys have been eroded out of a horizontal series of beds, the outcrops of the beds will follow the contours, encircling the hills and V-ing upstream at every valley.

This type of outcrop is admirably illustrated in many geological maps where the successive formations are coloured in different tints.

Let us now consider a little more difficult case, where the formations dip, instead of being horizontal. This introduces a problem.

There are two independent influences at work. There is a tendency for an upper formation to outcrop in the higher ground, and there is also a tendency for it to outcrop in the direction of dip. If the direction of dip is towards the high ground then the two tendencies will co-operate to put the outcrop of the upper formation on the high ground. If the direction of dip is away from the high ground then there is a struggle between the two tendencies and the stronger wins. That is, if the hill slope is steeper than the dip, then the upper formation will outcrop on the higher ground ; but if the dip, directed downhill, is steeper than the hill slope then the upper formation will outcrop on the lower ground (Fig. 13B).

Finally let us note what happens to the mutual boundary of the outcrops of dipping formations crossed by a valley of erosion. The boundary is deflected at a valley, but the direction of deflection is not always upstream as in the case of a geographical contour or of the outcrop of a flat bed. The V may point either upstream or downstream according to the relation which exists between the dip of the beds and the slope of the valley bottom. There is, however, one very simple rule to remember. The apex of the V in any valley points towards the outcrop of the overlying formation. This rule follows from the obvious relation that in the arms of the V, on the valley sides, the overlying formation occupies the uphill exterior position.

Let us note another very straightforward fact. If an outcrop crosses a valley with no deflection it must be vertical. A little common sense is required in applying this rule. A valley may be wholly cut in superficial deposits, in which case it has no effect upon outcrops underlying the superficial deposits. Also it may be impossible on a small-scale map to show deflections of outcrop that actually exist in Nature. Leaving these details aside we may sum up : horizontal formations follow the contours ; dipping formations pay less attention to them ; vertical formations disregard them (*cf.* Fig. 48).

CHAPTER V

PALAEONTOLOGY

PALAEONTOLOGY, the science that deals with the life of former geological periods, is based on the study of fossils. The word fossil, which denotes something dug up, was once applied generally to any kind of mineralogical or structural curiosity derived from the rocks, even if the object was not connected in any way with a once living creature. There is a tendency at the present time to apply the word fossil as an adjective to certain inorganic structures and phenomena such as fossil raindrops, fossil earthquakes, etc., but the scientific connotation of the term is now practically limited to the remains of animals and plants dug up from the rocks. By remains we mean not only preserved parts of animals and plants, but also evidences of their existence such as trails, burrows, castings, excreta (coprolites), footprints, pipes formed by rootlets, and so on. This limited meaning of the word fossil is still consistent with its derivation, but the term fossilisation, which ought to mean the act of digging up, is illogically used in modern practice for the process of preservation.

Although the science of Palaeontology is little more than a century old, references to fossils occur sporadically in philosophical writings from the time of the Hellenic civilisation. Thus about 500 B.C. Xanthus of Sardis drew attention to the occurrence of fossil shells in certain lands of the eastern Mediterranean and correctly concluded that the localities where such remains occur had formerly been submerged by the sea and that the limits of land and ocean were constantly undergoing change. Eratosthenes the Alexandrine and the Latin historian Strabo drew similar conclusions from the occurrence of fossil oysters in the Libyan Desert. During the Middle Ages little attention was paid to the subject of fossils, but with the revival of learning in the fifteenth century there began a long series of disputes concerning their nature. Some of the disputants regarded fossils as inorganic structures that either by accident or by Divine intention simulated the shells, bones and teeth of modern animals. The artist, philosopher, and versatile genius Leonardo da Vinci was prominent among those who championed the alternative, realistic and now prevalent view that fossils are the remains of once living organisms (see p. 3).

Early studies of fossils lacked co-ordination and system, and it was not until the end of the eighteenth century and the beginning of the nineteenth that Palaeontology was placed on a scientific basis largely by the work of two men—William Smith in England and Cuvier in France. Cuvier applied to the skeletons of fossil vertebrates the methods of comparative anatomy already used for the study of recent animals, and his work showed that many fossil animals were of types that no longer exist. To-day we regard this fact as almost axiomatic, and it is difficult for us to realise the enormous importance of its recognition in Cuvier's time, and the impetus that it gave to biological and geological research. William Smith (Fig. 312) was the pioneer in the use of fossils as markers of geological time.

The evidence of Palaeontology is of the greatest importance to the biologist in the study of evolution ; but to the geologist it is fundamental, because the geological time-scale is based on the succession of fossils in the sedimentary rocks. Geological events cannot be correlated with recurrent astronomical events to form a time-scale like our day, month and year. In geological history, except perhaps in what are called Pleistocene and Recent times, we do not date a rock formation in terms of years, with reference to some historical event like the birth of Christ ; we date it by the assemblage of fossils occurring in its sediments, assigning the formation to the particular division of the geological time-scale that is characterised by these fossils.

It was on these lines that William Smith established the first principles of Stratigraphy—the science that deals with the orderly arrangement of the sedimentary rocks and their geological dating. Smith was a mining engineer and mineral surveyor, and, in the course of his work in the neighbourhood of Bath, he observed that each of the formations represented in the local Jurassic rocks was characterised by a fossil assemblage that differed from those found in formations above or below. He was further able to show by means of the fossils that some of the formations recognised near Bath could be traced across England to the Yorkshire coast. These observations formed the basis of stratigraphical Geology, and demonstrated that there had been a succession of different faunas living in the English area during an important fraction of geological time. Later workers applied the principles enunciated by Smith in different regions and in other formations ; and the outcome was the construction of a more or less standard time-scale of geological history, based on the orderly succession of the fossils in the sedimentary rocks. Fossils have not equal value as time indices. The recognition of good time markers is a matter of observation and experience and depends on such factors as the range in time of the particular category (species, genus, etc.—see below, p. 31), the extent of its geographical distribution, and the number of individual fossils it yields.

System-Group		*System*		*Life*
Kainozoic (Recent Life)		Quaternary	Recent Pleistocene	Age of Man
		Newer Tertiary (Neogene)	Pliocene Miocene	Age of Mammals and the Modern Flora
		Older Tertiary (Palaeogene)	Oligocene Eocene Paleocene	
Mesozoic (Middle Life)		Cretaceous		Age of Reptiles and Ammonites
		Jurassic		
		Triassic	New Red Sandstone	
Palaeozoic (Ancient Life)	Upper	Permian		Age of Amphibia and Coal Flora
		Carboniferous		
		Devonian (Old Red Sandstone)		Age of Fishes
	Lower	Silurian		Age of Trilobites and Brachiopods
		Ordovician		
		Cambrian		
Precambrian				Age of unrecorded life and earlier

The major divisions of the standard time-scale are shown in the above table in the form generally used at the present day. These major divisions are subdivided again and again on a palaeontological basis, so that extremely refined correlations of strata are often possible. Very exact detailed knowledge of the stratigraphy of an area can thus be built up, and is of the greatest importance, not only in Pure Science, but also in proving and working natural resources like coal, oil, ironstone and building-stone.

Fossils in addition enable us to date in terms of the geological time-scale the great movements of the earth's crust that have modified the surface of the globe. They also supply us with much other information concerning the geography of past ages. For instance they afford evidence of the local physical conditions prevailing at the time of deposition, such as climate, depth and salinity of the water, presence or absence of strong currents, and other information about environment.

Only the hard parts of animals are really suitable for preservation—shells, bones, teeth, scales, etc. Usually the soft parts decay too rapidly for preservation, though in rare cases, under suitable conditions they may furnish excellent impressions and casts. Very rapid burial in extremely fine sediment is necessary, so that the form of the soft parts may be impressed on the sediment before they decay. Much the same holds in the case of plants. The fossil trees of Glasgow's famous Fossil Grove (Fig. 14) are sandstone casts taken by Nature from moulds or impressions of trees that rotted away after their lower parts had been buried in mud and sand.

Most shells consist of calcium carbonate, in the form of calcite or aragonite with an admixture of organic material. Here the word organic is not used, as above, in a purely biological sense, but as the chemist uses it—to indicate the complex hydrocarbon products that make up the body-tissues and fluids of living creatures. Bones are made of calcium phosphate together with organic material; the shells of crabs, lobsters and other crustacea, the shells of certain brachiopods, and the external skeletons of graptolites are composed of a horny substance called chitin that is similar to the material of finger-nails; while the hard parts of radiolaria, certain sponges and diatoms are siliceous. Fossil shells and bones are sometimes preserved in their original condition, where percolating water is excluded from the formation. In animals with chitinous skeletons, and in plants, a process of de-oxidation leads to a relative increase in the percentage of carbon, or carbonisation as it is called. In plants it gives lignite and coal, and in animals highly carbonised fossils of hard parts, *e.g.* the shells of crustacea.

FIG. 14. The Fossil Grove, Victoria Park, Glasgow. Sandstone casts of Carboniferous trees. (Glasgow Corp. photo.)

A common mode of preservation is called petrifaction. In petrifaction mineral material is introduced from solution in such a manner as to retain some of the structural features of the organism. In many cases a little original organic material remains in an altered condition, as for instance in the carbonised cell walls of certain silicified or carbonated plants. In other cases petrifaction has replaced all the organic and inorganic material, probably step by step, guided by the pre-existing structure. The commonest replacing substances are calcite, silica, iron pyrites and limonite.

In sandstones, percolating water containing carbon dioxide, CO_2, converts the calcite or aragonite to the soluble bicarbonate, and the original shell may be entirely removed, leaving only a mould, which may remain hollow or later furnish a cast in some foreign material.

The fossil record of past life is necessarily incomplete, apart altogether from the fact that it has only very partially been explored. Animals not possessing hard parts are practically unknown in the fossil state—*e.g.* most worms, jelly-fish, slugs, etc. Even hard parts decompose entirely, if not quickly buried. We have a much more complete record of prehistoric marine animals than of land animals, because in the sea and particularly on the continental shelf, with its prolific benthic (or bottom-dwelling) fauna, there is a good chance of burial by accumulating sediment, whereas on land burial of animals immediately after death depends on accidental circumstances—floods, sand or dust storms, trapping in swamps, etc.—and the hard parts are liable to be exposed until they decay. Occasionally, however, the accidental preservation of land animals has been almost unbelievably perfect. Mammoths are sometimes dug up in the frozen tundra of Siberia (Fig. 323) with their flesh in an eatable condition. Rhinoceroses are found mummified in the tar pools of Rumania (Fig. 15), and insects in amber, a fossil resin.

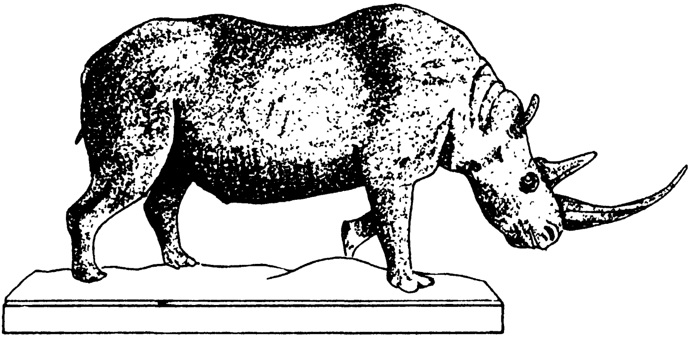

FIG. 15. Rhinoceros mummified by osokerite, excavated in 1929 in the clays at Starunia. (Acad. Sci. Cracow photo.)

Even the record of marine animals with hard parts is usually imperfect. By the oscillations of the crust consolidated marine sediments are elevated to form land, and then gradually, perhaps entirely, destroyed by weathering, together with their fossil contents. Sometimes the fossils prove resistant and may be incorporated in a later formation when they are known as derived fossils. They may be regarded as a special type of pebble. They furnish evidence of unconformity (Chapter IX), but are to be neglected in assessing the age of the later formations. Derived fossils may be recognised by signs of wear and tear (due to transportation) and by adhering fragments of rock-matrix that are foreign to the enclosing formation. As an example of derived fossils the thick-shelled Jurassic oysters known as *Gryphaea* often occur in Pleistocene boulder clay of the East of England.

In spite, however, of the imperfections of the fossil record, there is no great group of living or extinct animals whose skeletal structure and evolution is not known in outline; and some parts of the evolutionary story have been unravelled in remarkably full detail.

The largest divisions of the animal kingdom are called phyla. A phylum assembles all the creatures that have a common structural plan. Thus the vertebrates, *e.g.* mammals, fish, reptiles, birds, have all a backbone, consisting of separate bones (vertebrae), arranged in series.

Phyla are subdivided into classes, classes into orders, orders into families, families into genera, and genera into species. The species is the unit of classification. There is no agreed concept of the species, but for working purposes it may be defined as a collection of similar individuals capable of interbreeding and giving rise to fertile offspring. The latter criterion is not available to the palaeontologist in defining fossil species—he has to observe whether variation in a series of similar individuals is continuous or discontinuous.

A genus is a collection of species, having certain features in common (morphological definition), or it is a collection of species all derived from the same immediate ancestral stock (genetic definition). The genetic definition is more satisfactory than the morphological, and is the ultimate aim of all classification. In the study of any group of animals the morphological classification must necessarily precede the genetic.

The system of nomenclature for denoting a species is the binomial system usually ascribed to the Swedish naturalist Linné (Linnaeus). Modern systematic biology dates from the publication of the tenth edition of Linnaeus' *Systema Naturae* (1758). Any cases of binomial nomenclature published before that date are invalid.

In the Linnaean binomial system each species of animal or plant has a name consisting of two words—the first generic, and the second specific. The common edible oyster is called *Ostrea edulis*—*Ostrea* the generic name, *edulis* the specific, both in Latin or in Latin form. The initial letter of the generic name is always capital.

A generic or specific name to be valid must have been published with a description or figure; and it is advisable when an author is describing a species for the first time to name a specimen, or specimens, as types. These are carefully preserved, usually in a museum, to serve as the ultimate criterion for determination, because descriptions and figures are often inadequate. In museums, types are distinguished by small circular coloured labels.

It is often helpful to add the author's name after the specific name thus: *Ostrea edulis* Linné. In cases where a species, after definition, has been transferred to a different genus, the name of the original author is retained, but is placed within brackets. For instance, *Ostrea maxima* Linné has become *Pecten maximus* (Linné).

Certain other conventions are adopted. For instance in the explanation of Fig. 286, we find *Ogygiocaris* [*Ogygia*] *buchi* (Brongniart). In this case Brongniart named a particular trilobite *Ogygia buchi*, and for many years his action passed unchallenged so that geologists the world over became familiar with the title. Eventually, however, it was pointed out that the name *Ogygia* had already been given to a genus of moths, and that the trilobite all the time had been swimming, as it were, under false colours. Accordingly a new name, *Ogygiocaris*, was introduced for the dispossessed trilobite, but the now invalid name *Ogygia* may still be retained, if desired, within square brackets to minimise the confusion resulting from the change. Again, in the legend of the same figure, we may note *Orthis* (*Dinorthis*) *flabellulum* J. de C. Sowerby. In this case the name within round brackets, printed in italics with an initial capital, is of subgeneric rank.

In short, the specialists have a complicated subject to handle, and they have devised a code to express, in a few words and symbols, a very considerable amount of information. A beginner should not spend time in mastering the rules of procedure, but it will repay him to understand the principles or he may be confused, or even disgusted, by examples that he will meet in the course of his reading.

Subsequent chapters, XLIII-LVII, are designed to give the necessary zoological and botanical background for a study of fossils.

PART II

DETAIL REGARDING ROCKS, MINERALS AND STRUCTURES

CHAPTER VI

MECHANICAL SEDIMENTS

LET us now return to consider in more detail the various subdivisions of the sedimentary rocks, beginning with the mechanical.

DEPOSITS WITH BOULDERS AND PEBBLES.—Conglomerate, as already stated, is consolidated gravel. It consists of rounded pebbles derived from earlier rocks, often with sand filling the interspaces. Its pebbles have been transported and rounded by water, either by the flow of a river or by the waves of a sea or mighty lake. Thus, like most rocks, conglomerate carries a story for those who can read.

Breccia is a rock resembling conglomerate, only its fragments are angular instead of rounded. The word breccia is Italian and connected with our word break. Not all breccias are sediments, but many are. Sedimentary breccias generally originated as scree, or, as the Americans call it, talus. There is every gradation between conglomerate and breccia. This is nothing unusual. Many other rock types grade imperceptibly into one another. Thus pebbly sandstone stands as a link between conglomerate and sandstone.

Another bouldery deposit, very widespread in Britain, is called boulder clay or till, an old Scots word meaning clay. Boulder clay holds numberless boulders and pebbles of solid rock in an unbedded matrix of clay. The boulders can in many cases be proved to have come immense distances, even hundreds of miles. They are not rounded except at their angles, and they very often carry scratches similar to those shown by the rock surfaces in Fig. 1. The condition of the boulders, and the unbedded character of the matrix, give the deposit a distinctive character. Boulder clay to-day is being formed by glaciers in Switzerland and Norway. The boulder clay we find in Britain is certainly glacial in origin. Ancient consolidated boulder clay is called tillite. Examples are found in even more extraordinary geographical situations than that occupied by the boulder clay of Britain.

ARENACEOUS.—All kinds of sand deposits are called arenaceous, from the Latin *arena*, sand.

It is common knowledge that water currents, whether of rivers or waves, can round boulders and pebbles. Experience, however, shows that water cannot round small grains, unless they are of particularly heavy material. The grains as they become smaller lose the chance of acquiring much momentum from the comparatively slow currents that are all we find in water. Also the water acts as a cushion shielding the grains from impact against one another or against solid rock.

On the other hand wind can round sand grains, as is well known to any one who examines the larger sand grains of the Sahara. The wind travels at great velocities and does not furnish an efficient cushion to protect the grains of the sand blast which it carries. Think for a moment of the comfort of bathing among breakers on a stormy day. The sand in the sea does not cut one's skin. Contrast this with the discomfort of lying in the sand dunes behind the beach, with the blast biting into one's body.

Thus in Geology when we find a sandstone with well-rounded grains we are almost certain to find on considering the whole of the evidence that it has been derived from the sand of a desert, not a seashore.

It has already been explained that sandstone is consolidated sand, and mention has been made of the main types of cement responsible for its consolidation. Various important varieties of sandstone may now be enumerated.

Freestone is any rock which does not split preferentially in some particular direction and yet is easily or freely worked by saw or chisel in any or every direction. Thus sandstones, if they do not part readily along their bedding, and if they are held together by a soft though firm cement, are typical freestones. Freestone, however, is a builder's term, and refers only to the building quality of a rock, so that we must understand from the first that all freestones are not sandstones. In Glasgow the freestones commonly used are sandstone, but in London they are limestone.

Flagstone is very different from freestone, because its distinguishing character is the ease with which it splits along conveniently spaced bedding planes into slabs. The most typical flagstones are impure sandstones containing a good deal of clay material. They occur in great abundance in a formation called the Old Red Sandstone, where it outcrops in Caithness. The Caithness flags used to be worked in large quarries for export ; but the industry has now been ruined by the employment of concrete. The Caithness flags formed in a very extensive lake which often dried up. The flags very commonly show ripple marks and suncracks (Fig. 16).

Quartzite, like flagstone, contrasts strongly with freestone, but it is in regard to another property than bedding. Quartzite is very hard and intractible. It is a pure siliceous sand bound together with siliceous cement. It takes its name from the common crystalline variety of silica known as quartz. It is of little use for building, but is extensively quarried in Shropshire for road metal.

Arkose is a highly felspathic sandstone. A typical arkose is a pink rock mostly made up of quartz and felspar. Felspar is another common mineral, to be dealt with presently. Arkose, in a small specimen, may be difficult to distinguish from granite, which is for the most part made of the same two minerals, quartz and felspar. In arkose, however, the minerals occur as fragments, lying side by side, whereas in granite they have grown from fusion, and fit into one another. Also, in a big specimen, or in the field, one is almost certain to see bedding in an arkose. Arkose is largely developed in the North-West Highlands of Scotland, where it makes the country about Loch Torridon. Arkose and quartzose sandstone may both result from the destruction of granite ; but the conditions of derivation are different. The production of arkose from granite requires weather conditions that do not lead to chemical destruction of felspar. As we shall presently learn, a desert supplies such conditions, and it is probable that most arkoses have been produced under a fairly arid climate.

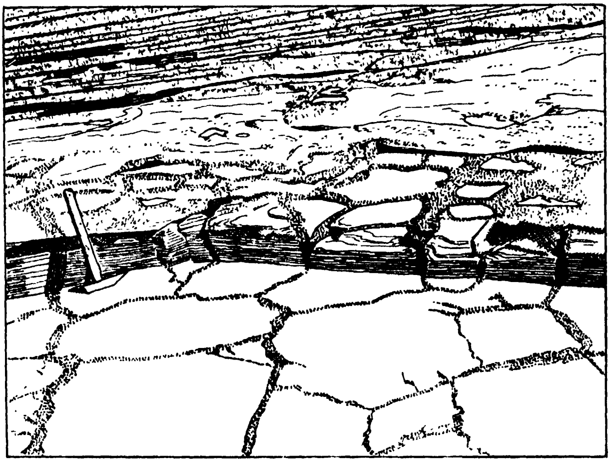

FIG. 16. Suncracks in flags, Thurso, Caithness. The cracks are filled with sandstone. (Geol. Surv. photo.)

Greywacke is a sandstone in which quartz, and generally quartz and felspar, are mixed with enough dark impurities to give the rock a grey colour. Greywacke is really a German word meaning grey stone. The term is seldom applied to any but very well compacted material. Greywacke is the commonest rock in the Southern Uplands of Scotland and in parts of Wales.

Grit is a term that is applied in several different senses. Some use it to mean a sandstone with big grains ; others to mean a sandstone with angular grains ; others again to mean greywacke. It is wise if you are writing a scientific account, and want to use the word grit, to explain in what sense you are employing it.

ARGILLACEOUS.—All the different kinds of clay rocks are grouped as argillaceous. The Latin word *argilla* means a white clay, but the geological word has nothing to do with colour.

Shale is the commonest form of compacted clay or mud. Its special character is its laminated style of bedding. A clay as originally deposited in water consists very largely of water, which when the clay dries is replaced by air, held in minute pores. The consolidation of clay under pressure squeezes out much of the water, or air, and accentuates the bedding. The presence of mica flakes deposited along the bedding is another very common feature that helps to make shale fissile, capable, that is, of splitting easily into thin layers.

The particles, other than mica, that go to make a clay, or a shale, are usually too small to be distinguished by the naked eye. Clay is typically a deposit of still bottom water. In the sea, which is the great repository of sediments, there is a belt of shallow coastal water that is disturbed by tides and waves. This has been called the Belt of Variables, because the nature of its deposits varies extremely according to local circumstances. It is here that on open coasts one commonly finds shingle or sand, with, in the tropics, coral reefs; while in sheltered estuaries one may encounter broad flats of mud. Outside the Belt of Variables, where the sea bottom extends to depths scarcely touched by tides or waves, conditions are more constant, and the coasts of the continents are surrounded by a broad belt known as the Mud Belt. Some of the clays of Geology are extremely extensive. There is a clay known as the Oxford Clay, which may still be recognised in many localities between the Hebrides and Switzerland. Thus we learn that much of western Europe lay within the Mud Belt of the sea bottom during the geological time that we call Oxfordian.

Oil shale is a variety of shale from which oil can be distilled in considerable quantities. Most shales contain a certain amount of carbonaceous material retained from the plants and animals, whose remains mingled with the original mud. In an oil shale this carbonaceous material is unusually abundant. The best known examples in the world occur in the East of Scotland, where they have given rise to an oil industry that has put up a wonderful fight with the free-oil industry of other countries. In oil shale the carbonaceous material is part of the solid rock; to get oil one must mine rock and then distil it, two expensive operations. On the other hand, the free oil, found in America, Persia and elsewhere, is stored in liquid form in the rocks, and comes gushing up when a hole is bored down to the underground reservoir. No wonder Scottish oil is hard put to it to compete with foreign oil, and it would have no chance were it not that oil shale yields ammonia on distillation, as well as oil, and this furnishes a valuable manure in the form of ammonium sulphate. It is naturally important to be able to distinguish oil shale from ordinary shale, without having to distil a specimen. Oil shale is of brown-black colour with brown streak; it is of leathery consistency and tends to yield a curly shaving when scraped with a knife. The word streak means the colour of a specimen reduced to powder. It may be observed on scratching a specimen with a knife, or on rubbing it against a rough surface of white porcelain, or again on powdering it and rubbing the dust on white paper. Scottish oil shales formed in freshwater lagoons or estuaries, and they owe most of their organic material to minute plants belonging to the algae (p. 354).

Mudstone is another type of consolidated clay-rock, distinguished from shale by absence of fissility, due to wider spacing of the bedding planes.

The name marl is used in two somewhat different senses. In the first it means an argillaceous rock without lamination, in which the consolidation is intermediate between that of a soft clay and hard mudstone. Such a marl on an exposed surface has a very characteristic habit of breaking up into small cubes about the size of dice. In its other sense marl stands for calcareous clay. At the bottom of pools or shallow lakes a shelly clay often accumulates, which largely consists of fragments of fresh-water shells. This deposit is called shell marl, and is sometimes used as a calcareous manure, that is, for liming fields.

We may complete our description of the truly sedimentary argillaceous rocks with a notice of one of the most widespread of oceanic deposits. In going from the shores of the continents we pass in succession a number of submarine zones, two of which have already been noted. The full succession is :

Belt of Variables
Mud Belt
Organic Belt
Red Clay Abysses .

Beyond the Mud Belt the waters of the ocean have lost almost all detrital material derived from the continents. Here the Organic Belt (Chapters VII and VIII) receives the remains of organisms that for the most part float, during life, somewhere in the superficial layers of the sea, and, after death, drop down like gentle rain or mist. They drop just as plentifully in the shallower waters of the Mud Belt as in the deeper waters beyond, but in the shallower waters their bulk is small compared with that of the mud from the land. On the deeper side of the Organic Belt the organisms also drop down ; but many of them, having to traverse miles of water, dissolve before reaching the bottom ; while the remainder perish on the bottom, where they lie long unprotected immersed in water with a comparatively high content of CO_2.

Accordingly in the deepest reaches of the ocean bottoms, the abysses as they are often called, there is neither terriginous nor organic sediment. There is in fact scarcely any sediment at all ; but a characteristic red clay does collect with almost incredible slowness (Fig. 17). It derives its material from the ash and pumice of volcanoes and from the fall of meteorites. It accumulates at such a leisurely pace that dredging brings up the remains of extinct and living creatures lying side by side on its surface. Amongst its commonest fossils are the ear bones of whales, often extinct. The rest of the skeleton has dissolved, leaving only the most resistant part.

Abyssal red clay has been elevated into dry land in Barbados, and may occur elsewhere, though its nature has been disputed. It is thought by many that, although land and sea have frequently changed places, the abyssal depths of the ocean have practically never been upheaved.

RESIDUAL DEPOSITS

Fireclay is a clay rock that withstands heat, or to use a technical word, is refractory. The definition is based upon industrial worth, and this in turn upon chemical composition. A fireclay is rich in aluminium silicates and poor in oxides of iron, magnesium, calcium and the alkali metals. In Geology fireclays are generally seat-earths of coal seams. In such case the bedding is obscured or destroyed by penetration of rootlets belonging to the plants that have yielded the overlying coal. The oxides that are in characteristically small quantity are the oxides which the plants have removed by sucking them up in solution for their own use.

Fireclay is almost always classed as a variety of sedimentary rock, but it does not wholly fall within the definition. Most fireclays were not deposited on the surface of the earth in their present condition, even apart from consolidation. They have derived their distinctive chemical characteristics through alteration after deposition. They are in fact fossil soils, they have lost much of their material; what remains is technically called a residuum, or less strictly, but much more commonly, a residual deposit.

Residual deposits are the insoluble products of rock weathering, which, having escaped distribution by transporting agencies, remain in place of the rocks from which they have been derived.

Soil is in large measure a residual deposit, mixed with decaying plant and animal matter, and with a variable proportion of added sediment, either wind- or water-borne.

The chemistry of a residual deposit depends partly upon the nature of the parent rock, and partly upon the climatic and botanic conditions to which this parent has been exposed. Much of the chalk of the South of England is covered with a residual deposit called clay with flints. In large measure it represents the insoluble residue of the chalk; and its flints are unworn—quite unlike the round flint pebbles of a conglomerate.

Where complex silicate minerals, such as occur in igneous rocks, weather under humid temperate climates, they tend to yield hydrated aluminous silicates, which are known collectively as the clay minerals. Under tropical or subtropical conditions chemical leaching often goes further, producing residuals of hydrated oxide of aluminium known as bauxite, and hydrated oxide of iron of the composition of iron rust. The resultant residual deposit, sometimes preponderantly aluminous, sometimes preponderantly ferruginous, is called laterite, from the Latin *later*, a brick, because, though soft enough to dig while damp, it hardens on exposure to very serviceable building material. In fact it furnishes the building stone and road metal of large tracts of India and Africa. The most aluminous forms of laterite, consisting essentially of the mineral bauxite, are themselves called bauxite. The name is derived from Beaux in the South of France, where ancient laterite has been largely worked as an ore of aluminium.

Ganister is the arenaceous equivalent of fireclay. Typically it is extremely rich in silica, and makes a good refractory.

CHAPTER VII

ORGANIC SEDIMENTS (CALCAREOUS)

LIMESTONE AND DOLOMITE.—Limestone, as already remarked, ranks first, in bulk at any rate, among organic sediments. It has many industrial uses ; being fairly soft, and yet firm, it makes a very valuable building stone, though subject to the attacks of weather ; it is the sole source of lime, much used in mortar, cement, agriculture and chemical industry ; it is employed as a flux in the extraction of iron from its ores, supplying lime to combine with siliceous impurities to give readily fusible slag.

The shelly and coral limestones are the easiest to interpret, for they are made up largely of the calcareous skeletons of creatures big enough to see with the naked eye. Such rocks have generally formed in the comparatively shallow waters of the Belt of Variables.

In the Organic Belt outside the Mud Belt the main calcareous shells that collect on the sea bottom belong to the foraminifera, which are always small and often microscopic. A very common genus is *Globigerina*. The resultant deposits cover wide extents of the ocean bed at great depths, and are so soft when accumulating that they are like mud to handle. They are called foraminiferal, or *Globigerina*, ooze (Figs. 17, 115). The Chalk is in large measure a consolidated foraminiferal ooze, and at one time it was thought that it must have formed at very great depths ; but more careful examination of the evidence has shown that it was a comparatively shallow water ooze. We shall go into this evidence later.

There are two different crystalline forms of calcium carbonate, calcite and aragonite. Living organisms may build their skeletons of either of these minerals, one type of creature developing the one, and another the other. Calcite, however, is the more stable of the two, and in actual consolidated limestone calcite is the form commonly found, whether as an original product or as a substitution for aragonite.

While many limestones are predominantly made of organic skeletons, whole or fragmentary, that can be recognised as such with the naked eye, most contain a certain amount of fine matrix, the organic origin of which may be disputed. It has evidently been a fine calcareous ooze or mud.

There are several ways in which such ooze may originate, of which may be mentioned :

(1) as a last stage in the breaking up of shells or corals ;

(2) as a chemical precipitate favoured by the life processes of bacteria ;

(3) as a chemical precipitate unconnected with life processes.

There can be little doubt that all three are important on occasion, but it may be a matter of difficulty to settle which has been followed in any particular case.

Recently a careful study has been made of the Great Bahama Bank in the West Indies, and interesting results have been published in the 1933 volume of the *Geological Magazine*. The Bahama Bank is a broad belt of shallow water bordering some of the West Indian islands. Its waters are evaporating more quickly than they are renewed by local rain and streams. Therefore they are maintained by inflow from the neighbouring deep ocean. Their salt content is higher than is proper to this neighbouring part of the ocean, and the conditions are such that $CaCO_3$ *must* be deposited, either organically or chemically, otherwise there would be supersaturation in respect of this compound. In keeping with this we find that there is a $CaCO_3$ deposit on the bottom, partly in the form of shell fragments, partly in the form of minute incoherent crystals of aragonite. Such crystals cannot themselves be shell fragments. They have obviously been deposited as independent crystals from solution. Further investigation shows that, while the deposit of these crystals may be in part quite independent of life, yet locally

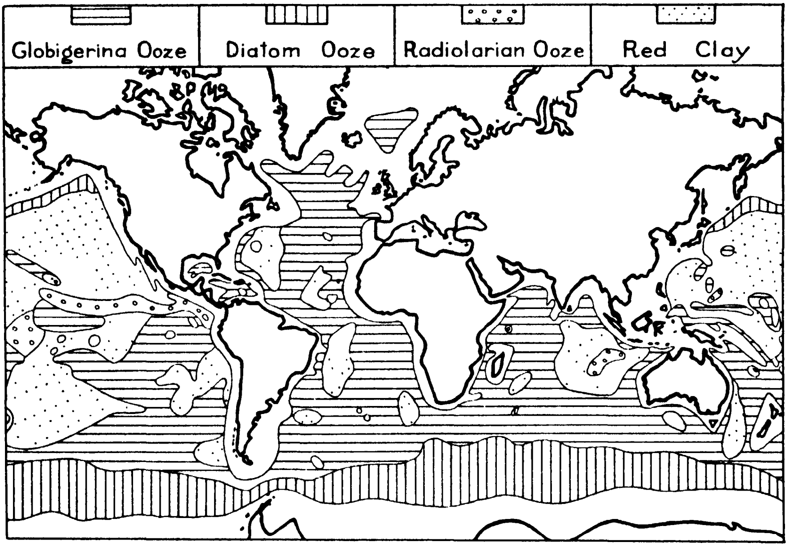

FIG. 17. The deposits of the oceans. (After Murray.)

it seems to be greatly helped by bacteria. The presence of suitable bacteria in large numbers has been demonstrated in mangrove swamps that often border the bank. The chemical reactions involved are varied and a little complicated, and those specially interested may refer to the paper itself. The formation of the minute crystals is probably spasmodic. Storms by stirring up the otherwise quiet sheltered waters of the bank give rise to intermittent precipitation of $CaCO_3$. Their effect is partly direct, for stirring helps crystallization, and partly indirect, for stirring also helps to liberate excess CO_2 from solution, and $CaCO_3$ is only soluble in water which contains CO_2.

As stated above most of the Bahama Bank is a sheltered sea, but there are tracts which are kept in almost continual motion by currents. Here the $CaCO_3$, instead of building minute incoherent crystals of aragonite, forms little spherical growths known as ooliths, because they look like fish eggs, and *oos* in Greek means egg and *lithos* stone. These little spheres grow by adding layer on layer while they roll about ; the layers at Bahama are made of aragonite. It is scarcely possible that bacteria have had anything to do with the precipitation of the $CaCO_3$ in this case, but certain authors in the past have claimed that films of seaweed (algae) grow on ooliths and help in their formation by decomposing CO_2 from the neighbouring water.

Ooliths of $CaCO_3$ have been found in process of formation in many other localities. The share algae have in their formation is disputed, but the clear fact is that they only form in warm water, moved by currents. Consolidated ooliths give rise to oolitic limestone, rare in Scotland but abundantly developed in England. It makes a very beautiful freestone, much used in London. St. Paul's Cathedral, for instance, is built of an oolite known as Portland Stone. An English name sometimes given to oolite is roe-stone ; the idea conveyed is again that of a stone with the appearance of fish-roe.

An argillaceous limestone is often called a cementstone, because on heating it gives a cement that sets under water. Nowadays cement is made from pure limestone, powdered and mixed with clay in the proper proportions and then burnt. The great cement of to-day is called Portland Cement, and the limestone used in its manufacture in Britain is generally chalk. The name Portland must not be taken to suggest that the cement has ever been made from Portland Oolite, but merely that the finished product at a distance looks something like Portland Oolite.

Cementstone of early Carboniferous date is an important rock type in the Glasgow district, where it cannot be claimed as made of the remains of plants or animals, for it is unfossiliferous. Instead it seems to have been a chemical precipitate, deposited in a lagoon subjected to intermittent evaporation. Possibly here, as so often, plant life co-operated in bringing about precipitation ; but if so, it has left no structure behind.

The Glasgow cementstones often contain much carbonate of magnesia in addition to carbonate of lime, the two combined in a double carbonate, $MgCO_3 . CaCO_3$, known as dolomite. The same feature is found in many other limestones, and these are said to be magnesian, or dolomitic. Quite commonly the double carbonate predominates, or occurs alone, and the resultant rock is itself called dolomite. The name is familiar on account of the beauties and climbing opportunities of the Dolomites of the Tyrol.

Dolomite as a rock looks very like limestone, but there is a simple chemical test ; dolomite will only dissolve in warm dilute acid, whereas limestone dissolves freely in either warm or cold dilute acid. Solution in either case is accompanied by effervescence or fizzing.

Dolomite is sometimes a good building stone, but if it has a little calcareous cement it may go to pieces in a town atmosphere. The Houses of Parliament, at Westminster, are built of dolomite, and though only 100 years old have required very expensive renovation, during which the weathered dolomite has been in part replaced by oolitic limestone.

The origin of dolomite is often difficult to decide. In the cementstones of the Glasgow district it was probably precipitated as such, when the rock was forming. In many cases, however, dolomite can be shown to have replaced limestone through chemical reaction of percolating solutions. For instance, fossils of a kind that must have started as calcium carbonate may now be found recast in dolomite.

CHAPTER VIII

ORGANIC SEDIMENTS (SILICEOUS AND CARBONACEOUS)

Radiolarian and diatomaceous deposits.—In introducing organic sediments mention has been made of microscopic marine animals with siliceous skeletons, called radiolaria (Fig. 118). To-day radiolaria are contributing to the formation of radiolarian ooze over wide expanses of the ocean beds (Fig. 17).

Let us recall the Organic Belt that intervenes between the Mud Belt and the Red Clay Abysses. In its shallower portions the Organic Belt is covered by preponderantly calcareous oozes made of foraminifera, while in its deeper portions it is covered by preponderantly siliceous oozes made of radiolaria.

The difference is due to the effects of solution. The foraminifera and the radiolaria live together in the surface waters. The forams, as they are often called for short, are the more abundant, and so tend to give their own character to the deposits that collect below. On the other hand the radiolaria are the less soluble, and where the water is particularly deep, their skeletons alone manage to reach the bottom, or at any rate to remain undissolved until blanketed by further deposit. If the water is deeper still, even the radiolaria dissolve, leaving the field clear, as we have seen, for abyssal red clay.

Radiolarian cherts are fairly common in Geology, and in some cases appear to have resulted through consolidation of abyssal radiolarian ooze, though in other cases they may be of shallow water origin. Radiolarian cherts often accompany submarine volcanic rocks, and it seems certain that submarine volcanoes, by furnishing siliceous solutions to the sea, give specially favourable opportunities for the growth of radiolaria.

Diatoms are microscopic plants with siliceous skeletons (Fig. 246). There are both fresh-water and marine diatoms. The marine forms flourish best where the oceans are fairly fresh and where glacial waters are supplying relatively abundant siliceous matter. Suitable conditions hold at present in the Antarctic Ocean, where much of the bottom is covered with diatomaceous ooze (Fig. 17). It is a remarkable fact that all the known examples of fossil diatomaceous ooze are of relatively recent date, which contrasts with the fact that many fossil radiolarian oozes are of extreme antiquity. It is probable that the simple diatom is a very ancient form of life, but the habit of building a siliceous skeleton may be a new acquisition.

Unconsolidated diatomaceous earth of fresh-water origin has been worked extensively on Deeside in Scotland. For a long time it was employed as an absorbent for the liquid explosive employed in dynamite. Marine diatoms in the seas around our coasts furnish the prime source of food for the herring. The diatoms are eaten by minute crustacea, which in turn are eaten by the herring.

PEAT, COAL AND OIL.—The outstandingly important carbonaceous rock is coal. It is derived from accumulations of plant material, and has a long history behind it.

At the present time peat is forming over wide areas. In temperate and cold countries it results mainly from the growth of mosses (such as *Sphagnum*), very common in Ireland and in the mainland of Scotland, or sedges (such as *Scirpus*), very common in the Outer Hebrides. Peat of this kind forms bogs on uplands or in hollows. Often the hollows are coastal swamps or fens.

In warm and tropical countries peat is accumulating from swamp growths of trees such as mangrove and cypress.

The accumulation of peat in the north is partly due to cold slowing down decomposition. The accumulation of peat in tropical swamps is partly due to heat speeding up growth. The coal seams of Britain, to judge by the nature of the vegetation, have been derived from tropical swamps.

The first step, from plant to peat, is due to bacteria, which lead to fermentation controlled and arrested by the products of reaction.

Peat can be converted experimentally into a glistening black coal-like substance by subjecting it to intense pressure at quite moderate temperatures.

Natural coal very often shows its planty constituents even on casual examination. When specially treated and looked at with a microscope, it reveals an unexpected wealth of vegetable structure. There can be no doubt that coal in its various stages is peat matured under pressure at moderate temperatures. The pressure is generally supplied by the weight of superimposed strata. The temperature rises a little with depth of cover. Sometimes pressures connected with mountain-making movements, and temperatures connected with igneous intrusions, lead to the extreme type of coal, namely anthracite, and even graphite.

The various grades, or ranks, starting with peat are: Peat, lignite, ordinary coal, anthracite, graphite.

In this list the percentage of carbon increases and the percentage of volatile constituents decreases. This last is shown by a drop in the percentage, not only of hydrogen, but also of oxygen and nitrogen.

As regards the different appearances of these varieties, lignite is generally browner and more obviously planty than ordinary coal; while anthracite is shinier and does not soil one's fingers ; and graphite is very soft and dirty, being the black lead of pencils.

In the great anthracite fields of Pennsylvania and South Wales, the coal has undergone gentle metamorphism in connection with mountain making. Graphite sometimes results as an extreme product of such metamorphism. In Scotland both anthracite and graphite have been produced to a small extent through metamorphism of coal by dolerite intrusions.

There is a special kind of coal called cannel, which contains an unusual proportion of volatiles, and also of argillaceous matter that on burning is left behind as ash. Such coal is duller in lustre than ordinary coal and breaks with a conchoidal fracture. On distillation it yields abundant illuminating gas, so that cannel is also called gas coal. In fact the name cannel is a corruption of candle, for good quality cannel coal burns like a candle when lit with a match.

At the end of the nineteenth century cannel was by far the most valuable kind of coal. Now that incandescent mantles are used, all that is needed is a heating gas, and cannel coal has lost its price.

Speaking in generalities, ordinary bright coal has originated through growth in place of the plants that go to form the coal, whereas cannel coal has originated through the deposit of a carbonaceous mud full of dirt and also of the minute water plants called algae ; it is, to use a common phrase, of drift origin.

The following table contrasts the properties of the two kinds of coal in a manner that illustrates their two modes of origin.

Growth in Place *Ordinary Coal*	*Drift Coal* *Cannel*
Small ash	Big ash
Extended and constant	Restricted and variable
Aquatic animals absent	Molluscs and fish present
Algae not abundant	Algae abundant
Rooty seat-earth general	Rooty seat-earth exceptional

Cannel coal is closely related to oil shale, but lacks the fissile structure.

During the concentration of peat to coal, there is an immense reduction of volume. Wet peat may contain about 80 per cent. of water. This introduces an interesting illustration of the need for caution in scientific interpretation. Sometimes a coal seam is found to enclose a band of sandstone, perhaps a quarter of a mile broad and many miles long, which in cross-section is flat-bottomed and arch-topped, with the bedding of the overlying material also arched. A leading authority in Yorkshire, where such occurrences have been carefully studied, thought that the sandstone had retained its original form, and interpreted it as a sand bank. This led him further. He claimed that the coal containing the supposed sand bank must have formed as a drifted deposit of vegetation, dropped in the water in which the sand bank accumulated. It has recently been pointed out by Kendall that the convexity of the upper surface of these sandstone bands is a secondary phenomenon due to shrinkage of the peat. The sand accumulated in a stream bed cut in peat (Fig. 18). At first it was convex downwards and flat on top. With shrinkage of the peat below, the marginal portions of the sand were lowered, so that the bottom of the sand became fairly flat and the top convex.

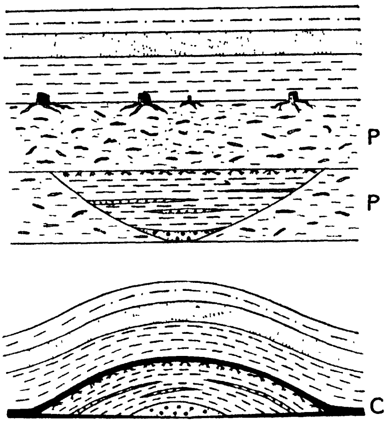

FIG. 18. Kendall's explanation of cross section of certain sandstone and shale bands in coal seams. P = Peat. C = Coal.

Since this explanation was given an unexpected confirmation has come from the modern fens of East Anglia. The photograph from which Fig. 19 is taken demonstrates a remarkable subsidence of fenland peat following artificial drainage, sometimes more than 10 feet in less than a century. Other photographs show that certain paths or broad lanes that now stand above the general level of the fens follow the courses of silt-filled stream beds, left high and dry by the shrinkage of surrounding and partially underlying peat (Fig. 20. It should be added that Godwin, *Geog. Journ.*, 1938, has denied the shrinkage illustrated in this figure). The photographs that have

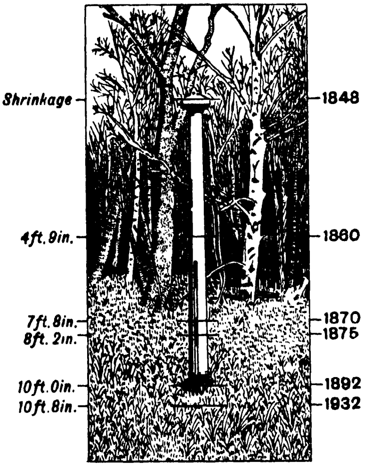

FIG. 19. Forty-eight per cent. shrinkage of peat, due to removal of water by drainage. The post has stood firm with its base grounded in silt. The depth of the contracted peat in 1932 was 11 ft. 4 in.

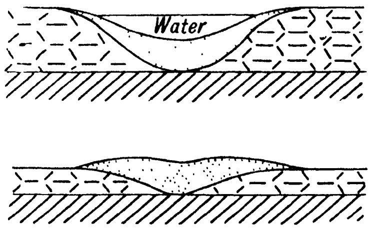

FIG. 20. Imaginary cross sections through mud and sand of a stream bed in peat, before and after drainage.

(Both figures after Fowler, *Geog. Journ.*, 1932.)

led to the interpretation of the paths as stream courses were taken from the air. In regard to this part of the story no question has been raised, but Godwin claims that the upstanding lanes owe their shape to original deposition, in fact that they are undeformed levées, a term explained in Chapter XXXII.

Mineral oil and gas are not rocks, but they are sufficiently allied to coal to warrant consideration here. There is practically no doubt that mineral oil and gas have mostly resulted from the decomposition of marine organisms, likely minute plants. The subject is very difficult, for oil and gas can migrate from rock to rock, and it is certain that the rocks which yield oil and gas are not as a rule those in which the oil and gas originated. Oil and gas are generally found in porous sandstones or fissured limestones, which act as reservoirs. It is probable in almost all cases that the oil and gas have originated in associated clay rocks.

CHAPTER IX

CONFORMITY AND UNCONFORMITY

BEFORE proceeding further with details regarding the formation of particular kinds of rocks, we may turn to a consideration of continuity and interruption in deposition. The subject is of the first importance in Geology. A series of deposits, whether sedimentary or volcanic, may be regarded as a book of history. If deposition has been continuous the book is complete ; if discontinuous, then pages or chapters are missing, and we must go elsewhere to fill the gap.

In undisturbed portions of the Mud Belt of the sea bottom, deposition of sediment may perhaps be regarded as continuous, though there are likely to be times of relatively rapid sedimentation alternating with other times of extremely slow sedimentation.

If a tract of the Mud Belt be depressed so as to enter the Organic Belt, or the Red Clay Abysses beyond, its sedimentation may still be considered as continuous, though the rate may become almost vanishingly small.

On the other hand, if a tract of the Mud Belt is elevated into the Belt of Variables, its sedimentation is likely to be definitely interrupted, at intervals, by current erosion alternating with current deposition.

If further the tract be raised above sea level, it is probable that its sedimentation will, on the whole, be overtaken by erosion.

With these considerations before us let us define and discuss certain terms which are constantly used in Geology.

Surface rocks, whether sedimentary or volcanic, are said to be conformable to one another, if their periods of deposition have not been separated by an interval of erosion.

Conversely they are said to be unconformable to one another if their periods of deposition have been separated by an interval of erosion.

The word unconformity is sometimes used to mean the surface that separates unconformable rocks, and sometimes the relation that exists between unconformable rocks.

Different kinds and degrees of unconformity are recognised :

(1) Unconformities are local or widespread according to the extent of country through which they are developed.

Local unconformities abound in current-bedded deposits. It is often the case that current erosion occurs at one point, while current deposition occurs less than an inch away.

Widespread unconformities are very common. The glacial deposits of Britain everywhere, except perhaps in Norfolk, rest upon an eroded surface of older formations. Many of the widespread unconformities of Geology record an advance of the sea over what has previously been a land surface. Such an advance is called a marine transgression.

FIG. 21. Angular unconformity. Lower Old Red Sandstone conglomerate resting on folded and eroded Dalradian, Kerrera, off Oban. (Geol. Surv. photo.)

(2) Unconformities are little or big according to the time interval that separates the deposition of the unconformable rocks.

Little unconformities, such as commonly occur in current-bedded deposits, scarcely interrupt the continuity of deposition, from the point of view of time. They are, therefore, often neglected in general statements of relationships. Thus a current-bedded sandstone, full of little local unconformities, may quite properly be included as an item in a conformable sequence.

FIG. 22. Disconformity. A, marls and sandstones of Trias; B, Upper Cretaceous conglomerate; C, Chalk. Murlough Bay, Antrim. (J. R. Welch photo.)

In a big unconformity the time interval represented by the unconformity may amount to very many millions of years. This is generally the case as regards the unconformity beneath the glacial deposits of Britain.

(3) Unconformities are angular or non-angular. Angular unconformity

is often called stratigraphical discordance (Figs. 21, 23), while non-angular unconformity has been named disconformity (Fig. 22).

In an angular unconformity sediments above and below the unconformable junction differ in dip. This relation may result, on a small scale, from irregular bedding due to currents or slipping ; but in many very important cases it chronicles a tilt by earth movement, followed by erosion, and finally a return of deposition. Such a history is a commonplace of British geology, where often we find a steep or even vertical formation overlain by another with gentler inclination. Classical examples occur in the River Jed, at Siccar Point and east of the entrance to Loch Ranza in Arran (Fig. 23). They were described towards the end of the eighteenth century by the same James Hutton, who interpreted granite.

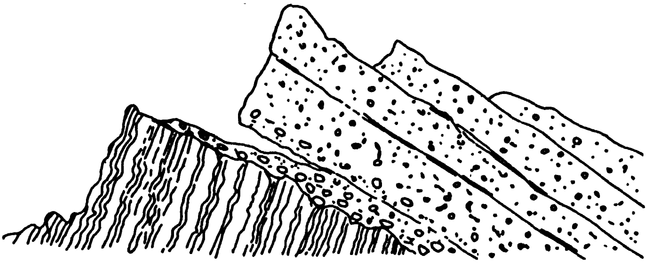

FIG. 23. Hutton's unconformity, Loch Ranza, Arran. (After Geikie.)

In a disconformity, sediments above and below the unconformable junction have parallel bedding.

Important disconformities are comparatively rare in Britain, because our country has had a restless history. On the other hand in the stable platforms, that are typified by the middle of North America or Russia, disconformities are abundant. In these platforms even the oldest fossiliferous rocks have not been tilted more than a fraction of a degree. They are hundreds of millions of years old, and have been elevated and eroded, but have scarcely any appreciable dip. It is common to find these flat ancient rocks underlying flat modern lake clays. The unconformity is immense, measured in years, but it finds no expression in a difference of dip.

Let us now consider the sort of evidence which helps us to recognise (*a*) conformity, and (*b*) unconformity :

(*a*) CONFORMITY.—(1) A conformable junction between two formations of different lithology is often marked by interbedding of the contrasted rock types, which indicates a passage or transition from the one formation to the other.

(2) A conformable junction is also suggested where there is continuity of fauna or flora.

(*b*) UNCONFORMITY.—(1) Angular unconformities are generally very easy to recognise. If the junction is exposed, and the angular discordance is considerable, the relationship is self-evident. Even if the junction is not exposed, an angular unconformity is usually clear once a geological map has been made, for the dips plotted on the map tell the story.

(2) An exposed unconformable contact between two formations is often recognisable as an erosion surface cutting irregularly across the bedding of the older formation.

(3) Erosion of an underlying formation previous to the deposition of an overlying formation is often indicated by pebbles of the former enclosed in the latter.

(4) Unconformity is often shown by a formation resting in different localities on different members of the earlier part of the succession. Where a member of a conformable sequence extends beyond its immediate predecessor so as to rest directly on older rocks, it is said to overlap its predecessor on to these older rocks. An unconformable bed, which passes across a series of older rocks, is said to overstep each of them in turn.

(5) Unconformity is suggested by a gap in the fossil sequence.

(6) Unconformity occurs wherever an unmetamorphosed sediment rests directly on an intrusive igneous rock, such as granite. Granite can only consolidate under cover. It metamorphoses its roof, as we call such cover. Therefore if it is immediately overlain by unmetamorphosed sediment we may be sure that erosion has removed the metamorphosed roof prior to the deposition of the unmetamorphosed sediment.

(7) Unconformity occurs wherever an unmetamorphosed sediment rests upon a distinctly metamorphosed rock. Metamorphism does not end abruptly. It always fades away. Therefore we can infer that a sharp unfaulted junction between metamorphic rocks and non-metamorphic sediment indicates erosion prior to the deposition of the latter.

(8) If a formation is unconformable to an intrusion, it must be unconformable to any sediments cut by this intrusion, if it happens to come in contact with such sediments. This criterion may be of great assistance in an intermittently exposed district.

CHAPTER X

MAP-READING

LET us return to the connections which exist between erosion and outcrops.

(1) As already stated, on a flat surface that has been eroded across a set of uniformly dipping formations, the outcrops of the formations succeed one another in parallel bands, each following its line of strike at right angles to the dip.

(2) An ordinary landscape is fairly flat in a broad sense, though cut into many hills and valleys on a relatively small scale. Therefore we can usually recognise the direction of strike on a geological map by noting the general direction of outcrop, leaving out of account local twists due to hills and valleys. Thus on looking at a geological map of England we see that the line of strike in Nottinghamshire is north and south and in Northamptonshire north-east (Fig. 24).

(3) Having recognised the line of strike we know that the dip is at right angles. Students very often think that the dip is always at right angles to the line of outcrop, but this is not the case. The line of outcrop may be tremendously affected by the local shape of the ground.

(4) The rule that dip is at right angles to strike is not enough in itself to fix the direction of dip, it merely limits it to one of two opposing directions. Thus if the strike is north and south, as in Nottinghamshire, the dip must be either east or west.

(5) The next rule to remember is that on level ground, or on ground that is broadly speaking level, the dip is from the underlying formation towards the overlying formation.

(6) Here we take advantage of the hills and valleys. They let us know at once which is the underlying and which the overlying formation. The relationship may be stated in two ways, either as a rule to be remembered, or as a deduction to be understood :

(6*a*) At a valley the outcrop of the underlying formation V's towards the outcrop of the overlying formation.

(6*b*) If we stand on some formation in the bottom of a valley and we see another formation above our heads in the two walls of the valley, then the formation exposed in the valley bottom underlies the formation exposed in the valley sides. This is a very simple common-sense way of looking at the matter and is invaluable in map-reading. Take as an example the formations numbered 20 and 21 in Northamptonshire (Fig. 24). No. 20 is seen showing through in several valley bottoms. It is therefore the underlying formation. We have already recognised that the strike here is north-east, and as the dip has to be at right angles to this, and as the overlying formation outcrops on the whole towards the south-east, the dip is now fixed as south-east.

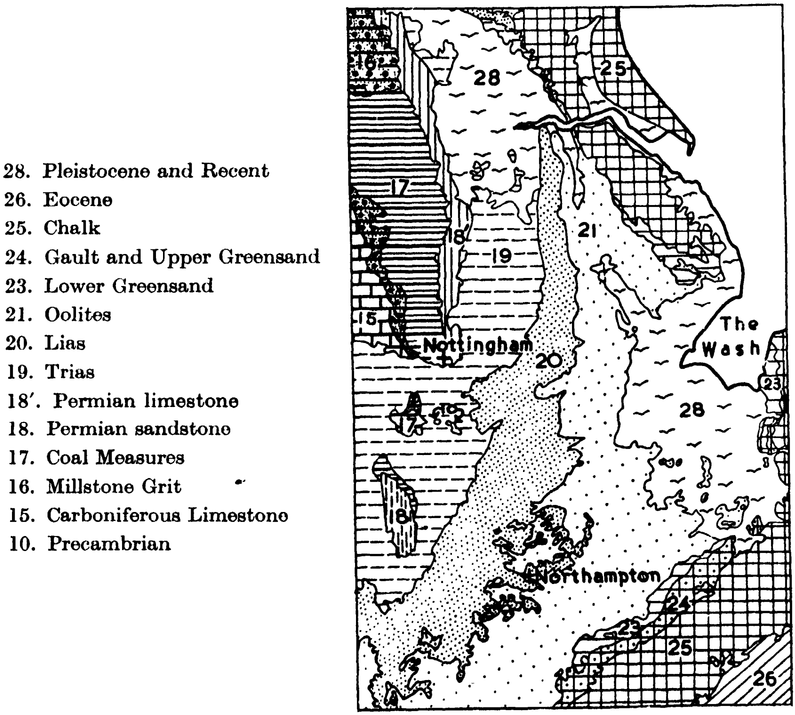

FIG. 24. Geological map of Nottingham and Northampton.

You will be well advised to buy the cheap and very interesting map of the British Isles published by the Geological Survey; and, once you have got it, play with it.

For instance:

(1) Draw a north-west and south-east section across Northamptonshire.

(2) Consider whether the evidence of succession obtained in Northamptonshire settles the order of succession in Nottinghamshire. Draw an east-west section across Nottinghamshire.

(3) Recognise the angular unconformity at the base of the Permian formation, from Nottinghamshire to Yorkshire (18′, Fig. 24).

(4) Understand the unconformable Recent and Pleistocene formations

about the Wash and Humber. They consist mostly of fenland peat and recent river sands and clays called alluvium (28, Fig. 24).

Up to this stage we have for the most part been considering outcrops that have a persistent dip ; but, as the strike changes between Nottingham and Northampton, it is obvious that the dip must also have swung round through an equivalent angle.

Let us now consider the outcrops of folded strata. In crossing a simple anticline or syncline we find no change of strike, but we do find a reversal of the direction of dip.

Let us start with an anticline striking north and south, that is an anticline in which the individual beds strike north and south. Suppose also that the ground is eroded flat. It is obvious that along the axis of an anticline the lowest, that is the oldest, of the exposed formations will come to the surface, while on either side higher, that is younger, formations will occur in a succession of outcrops running north and south (Fig. 12).

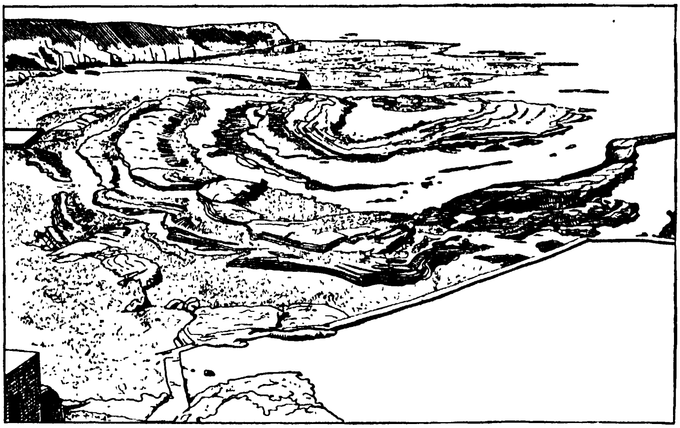

FIG. 25. Syncline in Carboniferous Limestone Series, Berwick on Tweed. (Geol. Surv. photo.)

In the case of a syncline just the opposite holds good. The youngest formation outcrops along the axis, and older formations flank it on either side (Fig. 25).

No anticlinal fold continues indefinitely round the globe, with everywhere beds dipping outwards from a central axis. Usually in both directions, separated by an interval which may be a fraction of a mile, or may be many miles, the limbs of an anticline swing round to meet one another with outwardly directed dip along the axis of the fold. In extreme cases, instead of having an elongated arch, or anticline, we have a circular arch, or dome. Dome, as a geological word, is defined as a fold in which the beds dip outward in all directions from a centre (Fig. 33).

Basin is the corresponding opposite. It is a fold in which beds dip inward in all directions towards a centre.

There are all gradations between anticlines and domes, and between synclines and basins. It is often a matter of choice whether we speak of some elongated dome as an anticline or a dome. This is illustrated in the well-known Wealden dome that brings Lower Cretaceous rocks to the surface in Kent and Surrey. It is a pronounced feature of the Geological Survey map of the British Isles. Note the oval distribution of the colours. It is excellent practice for you to make a copy of this part of the British map, and insert dips on it and draw sections across it. It is well worth while to get on friendly terms with geological maps. It not only helps to pass examinations, but to enjoy the country. There is no better companion on a hike than a geological map. Remember Geology is the great interpreter of scenery.

Good examples of basins are afforded by the coal basins of Lanarkshire and South Wales. The dark colour used for the Coal Measures shows up on the map of Britain even at a distance. Again it is good practice to copy these outcrops on to paper, and to insert dips and draw sections.

Now we are in a position to introduce two very common geological terms, inlier and outlier.

An inlier is an outcrop of a lower formation, or group of formations, completely surrounded by outcrops of upper formations.

An outlier is an outcrop of an upper formation, or group of formations, limited by erosion, and completely surrounded by outcrops of lower formations.

In the definition of outlier it is necessary to introduce the qualification : limited by erosion. A patch of recent clay, marking the bottom of a drained lake, is not an outlier, though probably surrounded by outcrops of lower formations.

On flat ground an inlier generally marks the outcrop of a dome. The Weald again furnishes a typical example, partly covered by the waters of the English Channel. Similarly on flat ground an outlier generally marks the outcrop of a basin. The South Wales Coal Measures constitute an outlier.

In a country cut into hills and valleys, inliers and outliers often occur without any dome or basin structure. Inliers tend to be exposed in valleys, and outliers on hill tops.

Here is a bit of advice as to the drawing of sections across the relatively simple maps that you are likely to study during your first year. Remember that changes of slope are much more numerous than changes of dip. There is a tendency for beginners to put higher formations everywhere into synclines. This holds well enough on the broad scale ; but, in detail, irregularities of outcrop are much more often controlled by the shape of the ground than by variation of dip. Bear this in mind, and use your intelligence. So far as possible draw steady dips in your sections with the help of a ruler, and adjust the surface to fit the exposures.

CHAPTER XI

COAL, WATER AND OIL IN RELATION TO STRUCTURE

GEOLOGICAL structure has an immense importance in matters of economic as well as scientific interest. It is common to talk of coal basins, for in many places once-continuous spreads of Coal Measures have been rendered discontinuous by erosion following folding. The tendency is for a formation to be removed by erosion, where it has been elevated into domes and anticlines, and to be preserved from erosion, where it has been depressed into basins and synclines.

Geological structure also largely controls the underground distribution of water. This is an important matter, with which we shall deal in detail presently (Chapter XXXI). Here it is only intended to introduce the subject, but even so it is necessary to define a few terms.

A rock is said to be permeable, or pervious, if water can pass through it under the influence of gravity at an appreciable velocity : the freer the movement, the higher the degree of permeability.

Rocks may be permeable for either of two reasons. An openly porous rock is permeable, and so also is a rock that is fissured.

Unfortunately some excellent geologists use the term porous as meaning permeable. This is a pity, for porous really means containing little cavities. Clay is porous. Quite a large part of the volume of a piece of dry clay consists of air contained in immense numbers of minute chambers or pores. Placed in water the clay slowly sucks in water until the pores are full. It is possible in this way to measure the porosity of a clay by measuring its increased weight on wetting. The porosity of clay is very high ; but clay is not permeable. Water may be drawn into clay by surface tension, but it can scarcely be got to move through this medium by gravity. Friction and adhesion virtually prevent water from filtering through so minutely porous a substance merely in response to its own weight. Thus clay, in spite of its porosity, makes an ideal impermeable lining for a reservoir. If a reservoir bed is cracked one can avoid leakage by puddling with clay.

Thus, while openly porous rocks like gravel and sand are permeable, closely porous rocks like clay are impermeable, unless they are crossed by open fissures.

Permeable rocks underground offer passages for the migration of water.

If they are covered and floored by impermeable rocks, the combination behaves like a pipe, in which the tendency is for the water to flow down at first to fill the lowest levels, and then to accumulate until it finds an exit. This affords an explanation of underground circulation of water. The rain that enters on the hill tops may be conducted in natural pipes for hundreds of miles to escape at last on the plains in springs. For the present it is enough to say that synclines and basins of permeable rocks furnish natural underground reservoirs for water; and that if the permeable rocks of these structures be overlain by impermeable layers the water contained in them may be under high pressure. For instance water enters the permeable chalk in hill country both north and south of London (Fig. 26). The chalk underground is underlain and overlain by impermeable clays. It is bent into a syncline passing below London. There it furnishes a reservoir. Several bores have been drilled through the impermeable cover to reach this great underground reservoir. Water in a system of pipes, whether natural or artificial, tends to reach its own level. Thus, when the bores tap the chalk under London, the water tends to rise to the level at which it is standing in the flanking hills. These hills are at a higher level than London itself, and accordingly when the first bores were sunk the water sometimes spouted out at the surface.

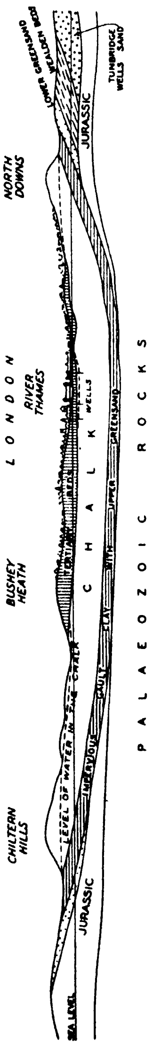

FIG. 26. Diagrammatic section across London Basin. (After Geol. Surv.)

Wells, in which water rises to the surface from deep-seated sources, are called artesian, from the province of Artois in France.

So far as London is concerned the happy days of true artesian wells have gone. Many wells have been sunk, and, as a result of pumping, each in time has become the axis of what is known as a cone of exhaustion. The general pressure has been relieved, so that at no point does water any longer get to the surface unaided : indeed, under much of London, the water level in wells supplied from the chalk lies 150 feet below sea-level. There is difference of opinion as to whether the London wells should still be called artesian ; probably it is better to speak of them as sub-artesian.

Before going on it is well to emphasise the self-evident fact that water will not automatically rise in a well any higher than the point at which it enters the ground. If you forget this, and you are an engineer, you may get no water. If you are a student answering examination questions, you may get no marks. So take care how you draw your sections.

We have already spoken of the underground migration of mineral oil and gas. These fluids traverse permeable rocks, and are held back by impermeable rocks. Their movements are in large measure controlled by the underground migration of water. Oil and gas float on water. Let us consider the consequences in two simple cases.

Think of a syncline of a permeable formation, with impermeable formations above and below, so as to furnish a natural pipe. Suppose that the syncline has been cut across by erosion, so that its pipe of permeable material comes to the surface on either side with an underground connection in between. Suppose also that the pipe was originally full of oil, but that its two open ends have long been exposed to rain.

Water supplied by the rain will sink through the oil, reach the bottom of the synclinal pipe, and there collect. It will gradually displace the oil, which must accordingly escape at the surface. Thus a syncline or basin will not furnish a permanent reservoir for oil, much less for gas. A bore under London has no hope of meeting oil or gas, only water.

On the other hand an anticline or dome often furnishes an ideal reservoir, for gas and oil. These light fluids, floating on water, tend to be driven up both limbs of an anticline and to collect in its summit arch, so long of course as there is a permeable formation covered by an impermeable formation to serve as pipe. In such a case gas is often found in the permeable formation at the crest of the anticline, oil farther down in the limbs, and water farther down again (Fig. 27).

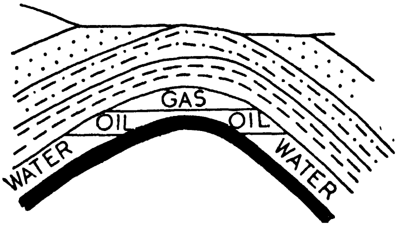

FIG. 27. Anticline showing distribution of gas, oil and water in a permeable formation.

The Weald dome of Kent is superficially of the right form to serve as a reservoir for oil and gas, but the conditions are complicated : the exposed formations have been tapped by post-dome erosion, while the concealed formations had already been drained in pre-dome times, when, as can be demonstrated, they suffered gentle synclinal folding and peripheral erosion. Still, gas obtained from a bore in the centre of the dome has for several years lit the railway station at Heathfield. Signal Hill, not far from Los Angeles, California, is in a much more productive condition (Fig. 28). It is an anticlinal excrescence, due to earth-movement of so recent a date that erosion has scarcely begun its work of levelling. Signal Hill had already been planned as a township, and divided into lots 25 feet by 25 feet, before geologists realised that it might be the landmark of an important subterranean reservoir of oil. When the first boring was rewarded by a gusher, the individual landowners drilled each his own hole, so as not to lose his share of the migratable wealth. The resultant congeries of bristling derricks furnishes a most impressive monument to unco-ordinated enterprise.

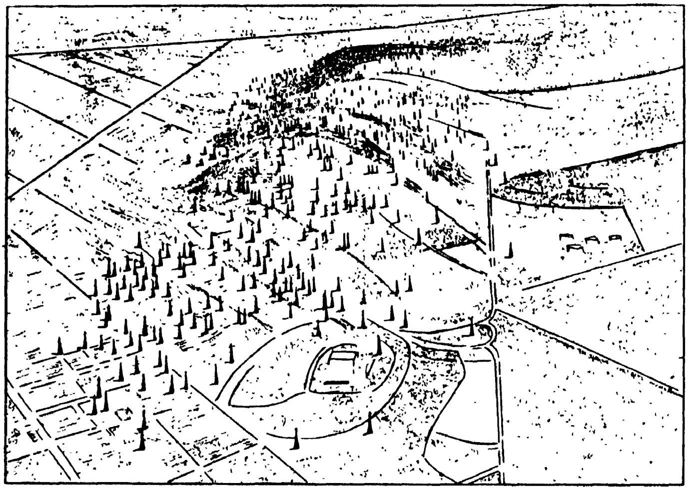

FIG. 28. The Long Beach Oil Field, California. The low ridge, Signal Hill, has been caused by a recent anticlinal uplift. (Aerial Surveys photo).

CHAPTER XII

MINERALOGY AND THE CRYSTAL SYSTEMS

Up to the present we have often used the word mineral without troubling about a definition. Like many other words it has more than one meaning. Even when employed as a noun, it has two very distinct meanings, one scientific, the other legal. It would be very foolish to suggest that one is right and the other wrong. They are both right in their own place. The difference is illustrated in the circumstance that coal and slate are not minerals in the scientific sense, but are minerals in the legal sense. We are at present concerned with the scientific definition.

A mineral is any natural solid, which can yield a homogeneous particle. There are two exceptions : glasses resulting from fusion are excluded ; so too are direct products of life, unless they are regarded as parts of fossils.

The connection between mineral and rock can be stated quite simply :

A single mineral, or for that matter, a glass, may make a rock, but only if it occurs in bulk : examples are furnished in exceptionally pure limestone and vein quartz, and (for glass) obsidian.

Most rocks are aggregates of minerals ; examples are afforded by limestone and sandstone, unless exceptionally pure, and by granite.

Minerals are either amorphous or crystalline :

Amorphous minerals are internally similar in all directions. They form a very small division, and the best example is opal.

Crystalline minerals are internally dissimilar in certain intersecting directions, though similar in all parallel directions.

The internal dissimilarities, referred to above as a distinguishing feature of crystals, can be detected in one or more of the following ways :

External shape.—If a crystalline substance had similar internal properties in all directions it would tend to grow as a sphere, but such is not the case.

Internal physical properties.—A crystal may differ, according to direction, in its thermal and electric conductivity ; in its transmission velocity for sound and light ; in its colour in polarised light ; in its hardness and cleavage ; etc.

Chemical properties.—A chemical corrosive sometimes etches figures of definite shape on a flat crystal surface.

Let us return to the question of external shape. Crystals occur in a multitude of shapes, which at first sight makes the subject appear hopelessly confusing. Study, however, has shown that these almost innumerable shapes can be referred to six, some say seven, crystal systems.

Before detailing the crystal systems, let us define a few terms :

The plane surfaces that bound crystals are called faces.

The lines, along which crystal faces meet, are called edges.

Any line, about which a crystal may be rotated into at least one other position of identical aspect, is called an axis of symmetry. It passes through the so-called crystal centre.

To understand all this more clearly, see what happens if you turn a cube about an axis drawn through its centre and connecting the mid-points of two opposite faces. The cube assumes an identical aspect four times during a complete revolution. In this case the axis of revolution is an axis of fourfold symmetry.

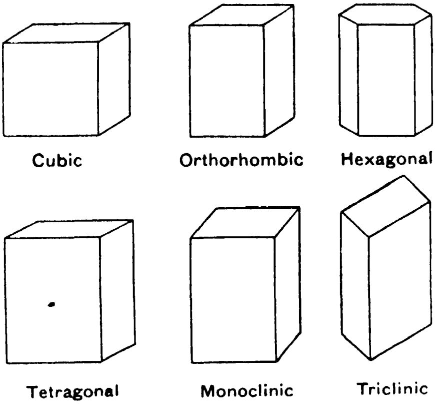

FIG. 29. The six crystal systems.

Description of the shape and other properties of crystals is greatly facilitated by reference to certain imaginary lines called crystallographic axes. These crystallographic axes are drawn through the centre of a crystal, either parallel to edges, or along axes of symmetry. Except in the case of the Hexagonal System, three axes and no more are selected. In the Hexagonal System it is convenient to take four axes. Whenever possible the axes are selected at right angles to one another and of equal length. Two axes are said to be equal, or of the same length, if they lie along directions possessing identical properties ; and they are said to be unequal, or of different lengths, if they lie along directions endowed with different properties.

We are dealing with the subject very lightly, but it is possible to illustrate it by considering two crystal models, a cube and an octahedron (Fig. 65).

It is particularly easy to understand that a cube can be referred to three equal axes at right angles, because it has three sets of edges at right angles and these edges are all equal in length.

In the case of the octahedron we can also choose three equal axes at right angles, because three precisely similar axes of symmetry lie at right angles to one another.

Let us now use crystallographic axes to define the six crystallographic systems (Fig. 29):

Cubic : three axes at right angles, all equal.

Tetragonal : three axes at right angles, two equal.

Orthorhombic : three axes at right angles, none equal.

Monoclinic: two axes at right angles to the third, and inclined to one another, none equal.

Triclinic : three axes inclined, none equal.

Hexagonal : three equal axes at 120° to one another in one plane, and a fourth unequal axis at right angles to this plane.

Crystallography will be dealt with in more detail in Chapters XXV and XXVI.

CHAPTER XIII

MINERALS GROUPED ACCORDING TO THEIR CHEMISTRY

CHEMISTRY is of fundamental importance almost everywhere in Science. One of the most surprising discoveries ever made is that the seemingly infinite variety of substances around us can be resolved into about a dozen elementary substances.

The elements are classed as metals and non-metals. There are only six really common metals in geology, and you will have to know their names and symbols: aluminium, Al; iron (Latin, *ferrum*), Fe; magnesium, Mg; calcium, Ca; sodium (*natrium*), Na; potassium (*kalium*), K. There are only two really common non-metals: oxygen, O, and silicon, Si. Oxygen is the great supporter of respiration and fire. Its compounds are called oxides: those with the metals are called bases, and those with the non-metals are called acidic, because on combination with water they yield acids. Three other less abundant non-metallic elements deserve mention, because of their great importance in Geology, namely: carbon, C; chlorine, Cl; and sulphur, S. Hydrogen, H, functions rather as an abnormal metal.

Not every acid contains oxygen. Two exceptions that we shall have to remember are hydrochloric acid, HCl, and sulphuretted hydrogen, H_2S. The really essential element in acids is hydrogen, H, which also occurs in water, H_2O.

Reaction between acids and bases, or combination between acidic oxides and bases, yields salts. Most rock minerals can be regarded as combinations between the acidic oxide silica, SiO_2, and one or more bases. Calcite, aragonite and dolomite, however, result from the combination of the acidic oxide carbon dioxide, CO_2, with one (or two) bases. Anhydrite and gypsum are sulphates, that is salts of sulphuric acid, H_2SO_4. Gypsum, it may be added, is a hydrated sulphate, where, as always, hydrated indicates the presence of combined water. Rock, or common, salt is a chloride, that is a salt of hydrochloric acid. Galena is a sulphide, that is a salt of sulphuretted hydrogen.

With this introduction it is possible to furnish a rough chemical classification of most of the common minerals of igneous and sedimentary rocks, leaving the ore minerals of veinstones for later consideration.

OXYGEN, O

Almost omnipresent, for there are only a few important minerals, such as rock salt and pyrites, that do not contain oxygen.

SILICON, Si

Igneous	*Sedimentary*
Quartz, hexagonal, SiO_2	*Quartz* reappears as fragmental grains, and is the most characteristic mineral of sandstones (many of the other igneous minerals reappear in similar fashion in sediments, but seldom need be mentioned in the lists that follow).
Chalcedony, including *Agate*, is cryptocrystalline SiO_2, deposited from solution in cavities, mainly the vesicles of lavas.	*Flint*, allied to Chalcedony, grows as nodules in Chalk. Some of its material is amorphous and soluble in potash.
	Chert, impure flint (often bedded) ② *Opal*, hydrated SiO_2 (amorphous)
Silicates	*Silicates*

One of the characteristic tests for silica, either as quartz, chalcedony, or flint, is its hardness. It is harder than a knife blade. Hardness is constantly employed in distinguishing minerals, and for rough purposes the finger nail and knife blade are the standards of comparison. For more accurate work a scale of ten divisions has been arranged, beginning with the softest. It will be noticed that, after the first two, which are softer than a finger nail, there follow four, which are softer, and four, which are harder, than a knife blade.

(1) Talc, hydrated silicate of Mg
(2) Gypsum, hydrated sulphate of Ca

FINGER NAIL

(3) Calcite, carbonate of Ca
(4) Fluorspar, fluoride of Ca
(5) Apatite, double fluoride and phosphate of Ca
(6) Orthoclase, double silicate of K and Al

KNIFE BLADE

(7) Quartz, silica, SiO_2
(8) Topaz, double fluoride and silicate of Al
(9) Corundum, oxide of Al
(10) Diamond, carbon, C

The chemical compositions are given largely to help in remembering the order. Nos. (1) and (2) are hydrous. Nos. (2)-(5) are salts of Ca. Orthoclase and quartz are easy to remember, either side of the knife blade. Nos. (8) and (9) are aluminous gems, for corundum, when suitably coloured, is called ruby or sapphire. No. (10) is the hardest and most valuable of gems, and is pure carbon. It is no accident that three gems—topaz, corundum and diamond—come at the hard end of the list, for it is one important characteristic of a gem that it should be hard and durable.

ALUMINIUM, Al

Igneous	*Sedimentary*
Most silicates, especially	*White Mica*, *Chlorite* and
Micas (monoclinic) and	*Kaolin* (monoclinic) and
Felspars (monoclinic and triclinic)	*Bauxite* (amorphous)

The micas may be grouped as white mica, or muscovite, a silicate of Al, K and H, and black mica, or biotite, a silicate of Al, Fe, Mg, K and H. They illustrate the fact that most of the mineral colouring of Nature depends on iron. The silicates are usually colourless, either transparent or white, if they contain no iron, and are coloured, or else black, if they contain iron. Another fact to remember is that in the silicates of igneous rocks iron is always accompanied by magnesium. Accordingly a convenient adjective, ferromagnesian, has been coined.

The micas also illustrate a property of crystals to which we have as yet scarcely referred, namely cleavage. Some crystals have the property of splitting along particular directions known as cleavage planes. If all the planes are parallel there is said to be one cleavage, and this is the case with the micas and chlorite, which both have exceptionally perfect cleavage (Fig. 30).

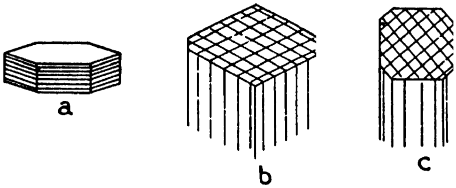

FIG. 30. Mineral cleavage.
a, mica ; b, hornblende ; c, augite.

Monoclinic felspar is a silicate of Al and K, and is called orthoclase. It has more than one cleavage, and when a felspathic rock like granite is broken the felspar cleaves and gives shining faces. This generally allows us to distinguish felspar from quartz, since quartz has no cleavage, and breaks like glass. Hardness also distinguishes the two.

Triclinic felspar is a silicate of Al and Na, mixed in variable proportions with a silicate of Al and Ca. It is called plagioclase, with various names determined by the proportion of Na to Ca. The Ca-rich species contain most Al. Plagioclase is very like orthoclase, but is distinguished by repeated lamellar twinning, which shows as parallel banding on a cleavage face.

Twinning is a regular intergrowth of individual crystals of one species.

Chlorite is a hydrated silicate of Al, Fe, Mg, without the K of biotite. It looks very like biotite, but is softer, scratching very easily with the finger nail. It is also inelastic, whereas biotite is elastic. It results from the alteration of ferromagnesian silicates such as biotite.

Kaolin is one of the clay minerals, a hydrated silicate of aluminium. It comes from the alteration of felspars, and in its purest form is the china clay of Cornwall, which has originated from granite through attack of natural steam. It is white and very soft.

Bauxite is hydrated Al_2O_3. It is a product of tropical weathering.

IRON, Fe

Igneous
Dark Minerals
Biotite, *Hornblende* and
Augite (monoclinic)
Olivine (orthorhombic)
Magnetite and
Pyrites (cubic)

Sedimentary
Dark Minerals
Chlorite, including *Chamosite* (monoclinic)
Glauconite (amorphous)
Haematite (hexagonal)
Limonite (amorphous)
Pale Mineral
Siderite (hexagonal)

We have already considered biotite. The next two minerals, hornblende and augite agree with biotite in being silicates of Fe and Mg with some Al; but they are easily distinguished, for both have double cleavage (Fig. 30). In hornblende the cleavage angle is about 60° (or 120°), and in augite about 90°.

Olivine is generally an olive-green and much less noticeably cleaved than hornblende or augite.

Magnetite and haematite are oxides of iron, Fe_3O_4 and Fe_2O_3. Limonite differs from haematite in being hydrated. Pyrites is sulphide of iron, FeS_2. These minerals have a property which is not shared by silicates. Their powder or streak is coloured. This is easily seen if we knock off some powder against the edge of a hammer and rub it on paper: magnetite has a black streak; haematite, red; limonite, yellowish brown; and pyrites black, although the mineral itself is a brassy yellow.

Magnetite has the further property that its powder can be picked up with a magnet.

Pyrites glitters like gold, but even a beginner in Geology can tell the difference if he tests for hardness. Pyrites will not scratch with a knife, whereas gold cuts. Also pyrites when rubbed on unglazed porcelain, leaves a black streak, but gold a golden yellow streak.

Chlorite in sedimentary rocks has mainly resulted from the weathering of igneous ferromagnesian silicates. Chamosite, however, grows on the sea floor as ooliths. It is an uncommon, but important, hydrated aluminium silicate of Fe.

Glauconite is a dark green hydrated silicate of Fe and K, which under certain conditions is produced in small grains on the sea bottom. It is generally interpreted as a chemical precipitate, but has recently been claimed as a submarine alteration product of biotite. It is commoner than chamosite, and both ancient and modern glauconitic greensands are well known. Glauconite looks like chlorite (including chamosite), and is almost as soft, but can be distinguished chemically and optically, that is with a microscope.

Siderite is iron carbonate, $FeCO_3$. Like dolomite it dissolves with effervescence in hot hydrochloric acid, while little affected by cold acid. It can be distinguished from dolomite by its greater specific gravity and its chemical reactions. It is not clear and colourless, as calcite so often is, and its lack of reaction with cold acid distinguishes it at once. It frequently occurs in argillaceous beds or nodules known as clay-band ironstone, which is the iron equivalent of cementstone.

MAGNESIUM, Mg

Igneous	*Sedimentary*
Always *accompanies* Fe in the *silicates*, and is especially abundant in *Olivine* (orthorhombic) Secondary minerals are *Chlorite*, *Serpentine* and *Talc* (monoclinic)	*Chlorite* and *Serpentine* (monoclinic) *Dolomite* (hexagonal).

Serpentine and talc are both hydrated silicates of Mg. There is generally enough Fe associated with serpentine, either in combination or mixture, to colour it. Serpentine may occur in bulk, that is as a rock, in which case it has usually resulted from the alteration of olivine-rich igneous rocks. Its hardness is about equal to that of calcite (3 of the scale), and as it takes a good polish, and stands the weather it is much used for ornamental purposes. Talc of course is much softer (1 of scale) and is greasy to the touch. Some of you have met it in the form of powder. Rocks composed largely of talc are called soapstone, and are much employed in Norway in building fireplaces in wooden houses. Dolomite, $CaCO_3 . MgCO_3$, has been described in connection with limestone (p. 45). It is employed as a refractory lining for furnaces.

CALCIUM, Ca

Igneous	*Sedimentary*
With Fe and Mg in	*Calcite* (hexagonal)
Hornblende and *Augite*	*Aragonite* (orthorhombic)
(monoclinic)	*Dolomite* (hexagonal)
With Al and Na in the	*Anhydrite* (orthorhombic)
Triclinic Felspars	*Gypsum* (monoclinic)

The calcium-rich triclinic felspars are called anorthite, bytownite and labradorite. With increasing sodium they are called andesine and oligoclase. Labradorite is named after Labrador, where it often possesses iridescence; but this is by no means a necessary feature of the mineral. Andesine is named after the Andes.

Calcite, calcium carbonate, $CaCO_3$, and dolomite, $CaCO_3 . MgCO_3$, have been mentioned frequently already. All we need remember about aragonite is that it is an alternative crystalline modification of $CaCO_3$.

Anhydrite is the anhydrous sulphate of calcium, $CaSO_4$. It is found in great abundance in geological deposits formed under desert conditions ; this is a matter to which we shall return presently (Chapter XV).

Gypsum, $CaSO_4 . 2H_2O$ is very commonly deposited to-day in desert environment. It also results from oxidation of iron sulphide in the presence of calcite in marine clays. Its cleavage and softness help us to recognise it.

SODIUM, Na

Igneous	*Sedimentary*
Albite (triclinic)	*Rock Salt* (cubic)

POTASSIUM, K

Orthoclase (monoclinic)	*White mica*, both fragmental and secondary (monoclinic)
Microcline (triclinic)	*Glauconite* (amorphous)
Micas (monoclinic)	*Sylvine* (cubic)

Albite is the pure soda felspar of the plagioclase series. It is a double silicate of Al and Na. It is distinguished from the Al-Na-Ca members of the series by optical tests and lower specific gravity. It is distinguished from orthoclase by lamellar twinning.

Orthoclase is the corresponding potassium felspar (silicate of Al and K), which, though it belongs to a different crystallographic system, has very nearly the same crystal shape and cleavage. It differs in not having lamellar twinning.

Microcline is identical in composition to orthoclase, but has cross-twinning.

Sodium and potassium are very closely allied in their chemical properties. One of their important differences is the ease with which potassium forms micas in igneous and metamorphic rocks. Of these, white mica or muscovite is extremely stable. Not only does it resist destruction, once formed, but also it readily develops, on a minute scale, when potassium felspars are altered by weather. Accordingly muscovite is stored up in sedimentary rocks, where in accordance with its flaky character it gets wafted by gentle currents to the Mud Belt. In fact potassium tends to accumulate in argillaceous sediments, while sodium, which does not readily form micas, passes into solution and is the outstanding metal in sea water.

Rock salt is sodium chloride, $NaCl$. It is very frequent among desert deposits, ancient and modern. It is distinguished from other soft cleavable minerals that you handle by its taste.

Sylvine is potassium chloride KCl. It too has a strong salt taste, but you are not very likely to meet it. It occurs as a very rare constituent in desert deposits, and is only found in bulk at Stassfurt and other German localities, where it is worked as a manure; for, broadly speaking, plants require potassium, whereas animals require sodium. The rarity of sylvine is connected with its extreme solubility, as well as with the comparatively small amount of K that occurs in sea and other natural waters.

No attempt has been made to tell all that should be known, even by a first-year student, about the minerals that have been listed. Much information should be acquired by handling specimens and at the same time consulting more special treatises.

CHAPTER XIV

CHEMICAL SEDIMENTS ELSEWHERE THAN IN DESERTS

We now pass to the last group of sediments, namely, the chemical precipitates.

Water is classed as hard or soft according as it yields a lather with soap with difficulty or with ease.

London has hard water, Glasgow soft.

Hardness is due to the presence of salts of calcium and magnesium in solution, since these form insoluble precipitates with soap solution.

Where the salts are bicarbonates, $CaCO_3 . H_2CO_3$ or $MgCO_3 . H_2CO_3$, they are decomposed by boiling, and the simple carbonates precipitated. Hardness due to these easily decomposable salts is termed temporary.

Where hardness is due to sulphates or chlorides, which do not decompose on boiling, it is called permanent.

Calcareous and siliceous.—The kettles of the London district are, or were, often lined with $CaCO_3$ (much of the water is now artificially softened). The hardness of London water is largely due to bicarbonate of Ca, picked up from the Chalk. All natural water, for instance rain water, contains some CO_2 and can convert limestone into soluble bicarbonate until saturation is reached. The Loch Katrine water supplied to Glasgow is soft because there is no limestone in its drainage basin.

We shall later follow the solvent power of water containing CO_2, leading to the production of caves in many limestone districts of the world. At present we are concerned with chemical deposition, rather than chemical erosion. In Nature we constantly find a tendency towards balance of opposing principles. For instance erosion often proceeds to such an extent that a small change in conditions leads to deposition. Thus in limestone caves, which are a product of erosion, we almost always find growths of calcite, which are a product of deposition. We must remember that water may enter limestone from a planty soil, which raises its CO_2 content to a comparatively high figure. Such water dissolves a correspondingly large supply of $CaCO_3$ as bicarbonate. If presently it is exposed to an atmosphere that allows of loss of CO_2, or alternatively of H_2O, as is the case in many ventilated caves, deposition will follow. The resultant growths take two particularly common forms:

Stalactites, which are pendants from the roof, and stalagmites, which are spires built up from the floor.

In both, the internal structure is the same. A cross-section shows concentric layers of growth, with radiating fibrous prisms.

Stalactites are formed by drip from the roof. The deposit starts actually on the roof of the cavern. It grows through the years and slowly develops into a pendant reaching downward.

Stalagmites are formed in analagous manner, where the drip splashes on the floor. In course of time a stalactite and stalagmite may unite in mid air to form a continuous column.

Calcite is frequently precipitated on the surface of the ground by springs issuing from limestone. The resultant deposit is characteristically porous and is called calcareous tufa, calcareous sinter, or travertine. It takes its name sinter from the German for cinder, on account of its porous texture. It is of common occurrence in many limestone districts. While Scotland has little limestone except in the North-West Highlands, England has much, for instance in the Pennines. Springs depositing travertine are sometimes called petrifying springs. The travertine grows rapidly, and if a bird's nest or handful of moss is put in such a spring, each fibre gets coated with calcite in a year or two, so that the whole is turned to stone. Such curiosities are sold to tourists.

Hot springs coming through limestone may deposit great masses of travertine, and the rock may be compact enough to serve as excellent freestone. Rome is largely built of travertine. The United States employs it for many big structures, and London is taking to the habit. On a broad scale travertine is very handsome. Glasgow imports a little for ornamental borders to shop fronts, but the effect may be disappointing.

The Mammoth Springs in the Yellowstone Park exhibit a feature often shown at hot springs. They have deposited calcareous tufa with a very irregular domed surface that supplies rims to a terraced succession of basins (Fig. 31). The explanation is as follows: Suppose hot calcareous water spreads slowly outward from a spring over a flat surface. It cools and evaporates, and at a certain distance from the source begins active deposition, thus eventually building up a wall enclosing a basin. The wall once made tends to increase, for the water slowly trickling down its surface is cooling and evaporating more advantageously than in the basin behind. Outside the wall the water has to flow a few additional feet or yards, before cooling and evaporation bring it once again to a supersaturated condition of active deposit. Thus basin after basin is formed at successively lower levels.

Simple water plants called algae flourish in these hot springs, and by decomposing the CO_2 in solution help to break up the soluble bicarbonate. The importance of their share in forming travertine is a rather open question.

Siliceous sinter is a porous cinder-like deposit of opal formed by alkaline hot springs. It is a rare rock except in the geyser districts of Iceland, the Yellowstone Park and New Zealand. In each case the springs are coming through lava of a type known as rhyolite that by decomposition readily yields opal. In New Zealand the siliceous sinter built a wonderful succession of basined terraces, known as the Pink and White Terraces, now destroyed by volcanic explosion. They were like the calcareous terraces of the Mammoth Springs, explained above. Plant life co-operates in the formation of siliceous sinter, but it is doubtful whether it is important.

The calcareous and siliceous sinter of hot springs are both deposited from clear water. There is another very highly characteristic deposit, often found in the hot springs of the Yellowstone Park, namely mud. Here one finds the paint pots or mud volcanoes, as they are called, with steam bursting in mighty bubbles through material of the consistency of porridge.

FIG. 31. Terrace basins of calcareous sinter, Mammoth Springs, Yellowstone Park, U.S.A.

The Carnegie Institute has recently investigated the calcareous, siliceous and mud springs of the Yellowstone Park. Below is a granite mass, cooling slowly and giving off steam with abundant CO_2 and some H_2S. Where these gases come up through limestone, the main reaction leads to solution of the bicarbonate, $CaCO_3 . H_2CO_3$, which affords ideal conditions for the subsequent deposition of calcareous sinter. Where the gases come up through rhyolite, their effect depends upon how much water they meet and at what depth :

(1) If the gases meet plenty of water, well below the surface, they are cooled quickly in the absence of air, and their H_2S escapes oxidation. The CO_2 weakly attacks the rhyolite giving an alkaline solution of Na_2CO_3, and this dissolves a little SiO_2. The total action is small and the water remains clear. On cooling and evaporation opal is deposited.

(2) If the gases only meet a little water, and that near the surface, the H_2S is oxidised to H_2SO_4, which actively attacks the rhyolite giving Na_2SO_4, at the same time producing a mud of kaolin and opal powder.

These hot springs are wonderfully numerous and wonderfully widespread and wonderfully interesting in the Yellowstone Park. Probably some day within the next few thousand years much of the park will go sky high in a volcanic explosion.

FERRUGINOUS.—Iron exists in solution in some natural waters as bicarbonate, $FeCO_3 . H_2CO_3$. If this loses CO_2 under conditions which prevent oxidation it is deposited as granules of siderite, $FeCO_3$. Thus have resulted many of the clay-band ironstones, commonly found in formations that carry coal seams; clay-band ironstone is very like cementstone, only with Fe instead of Ca. In some clay-band ironstones, known as mussel-band ironstones, there has been replacement of calcareous shells by $FeCO_3$. Black-band ironstone is the same as clay-band, but is black through richness in carbonaceous material derived from plants. Clay-band and black-band have been the most important forms of iron ore found in the coal-bearing strata of Britain. Black-band is particularly valuable, as its carbonaceous material decreases the necessity for coal in the processes of extraction.

If the iron carbonate in solution oxidises it yields limonite. This often furnishes a spongy deposit on lake bottoms, known as bog iron ore, much used in Norway and Sweden. Bacteria play an important part in the precipitation of bog iron ore.

Chamosite and glauconite have already been referred to somewhat fully in the mineral list. It may be added that chamosite is responsible for some very important iron ores, such as the Cleveland ironstone of Yorkshire and the Raasay ironstone of the Hebrides. Until recently it was thought that the Cleveland ironstone had been formed as an oolitic limestone and later converted into ironstone by percolating solutions; but this is now known to be a mistake.

CHAPTER XV

CHEMICAL SEDIMENTS OF THE DESERTS

THE remaining chemical deposits are those which have resulted from evaporation, especially under desert conditions, of partially severed arms of the sea, or of inland lakes without outlet, such as the Dead Sea and Great Salt Lake. Where inland lakes receive much of their water from the drainage of sedimentary rocks, their salt deposits are similar to those of the sea—probably because they are collecting old sea salts washed in minute quantities out of the sediments.

The commonest chemical deposits in such situations are :

$NaCl$	*Rock salt*
$CaSO_4 . 2H_2O$	*Gypsum,* called *Alabaster,* where pure, finely granular, and suitable for carving
$CaSO_4$	*Anhydrite,* abundant in ancient, but not in modern, desert concentrates
$CaCO_3$ and $CaCO_3 . MgCO_3$	*Calcite* and *Dolomite,* in such deposits as the cement-stones of the Glasgow district.

Where drainage enters modern desert lakes after traversing crystalline rocks, rather than sediments, sodium carbonate, Na_2CO_3, is often deposited.

Many geological formations contain rock salt. They clearly indicate desert conditions of evaporation. Gypsum is a characteristic associate of rock salt and is considerably more abundant. This is in keeping with the fact that it is less soluble and therefore more easily precipitated. In depth many of the gypsum deposits of Geology give place to the dehydrated sulphate, anhydrite. If gypsum is exposed to water under a pressure of about 30 atmospheres, it changes to anhydrite ; or, alternatively, if calcium sulphate is precipitated under these conditions it appears as anhydrite. In Nature only gypsum has as yet been found in process of deposition. Nevertheless those who know anhydrite deposits best think that the anhydrite was deposited as such, because they can see no evidence of shrinkage. It is well to remember, however, that there is little ocular evidence of shrinkage in connection with a coal seam, and it seems possible that anhydrite in Nature is mainly a subterranean condensation product of gypsum under pressure. The reverse process, the hydration of anhydrite, is a commonplace in Nature, in regions with underground circulation of water. The swelling effect is very obvious, for it crumples up the bedding of the resultant gypsum or leads to concurrent veining. Gypsum is used in commerce as a source of plaster of Paris—a powder containing partially dehydrated sulphate obtained by heating. On adding a little water the powder sets to a firm cement of gypsum.

Sylvine, KCl, as already stated, is very rare on account of its great solubility.

All these soluble salts not only require extreme conditions of evaporation for their deposit, but also favourable conditions of entombment for preservation. It is essential that they be protected with an impermeable cover, and it is necessary that they be not exposed to circulating waters. It is sometimes found that they are completely washed out, or leached, from formations which, standing above sea-level, have been exposed to circulation, although they may be preserved in the same formations in depth. Stagnant conditions, such as favour the underground preservation of oil and gas, also favour the preservation of salt. Thus water underlying oil is often brine.

Salt is mined in some districts. In others it is brought up to the surface in solution. Water pumped down is recovered as brine. In Cheshire subsidences due to extraction of salt in this fashion have given rise to several small lakes.

Common salt is one of the great necessities of animal life. This is not so obvious in our islands where salt is blown over the pastures from the surrounding seas. In some of the interior States of America it is laid down by law that salt must be fed to cattle. The reason is that our blood and other juices are salt solutions. It is known that our early ancestors were marine. When they crawled out of the sea, they had, unconsciously of course, to maintain marine solutions for their cells to live in. Thus we see that the Salt Tax of India is connected with our evolutionary history very many millions of years ago.

Another feature of interest about common salt that has forced itself upon scientific attention during the last thirty years is the tendency of buried salt beds to flow together towards centres and form domes. Salt domes have been investigated in India, Persia (Iran), Rumania, Germany and the Gulf region of America. Salt is soft and light, in comparison with other rocks, and so tends to work its way up to the surface like a viscous fluid. On the way it arches and pushes aside the neighbouring rocks. In many cases salt beds seem to be able to lie dormant for long geological ages. As a rule it appears that salt migration is started by earth movements of the type responsible for the folded structures of mountain chains such as the Alps. In the Gulf of Mexico region, however, there is no sign of mountain folding. There has been only a gentle tilt of the formations followed, or accompanied, by erosion. This has left a wedge-shaped load of formations on the back of the salt layers; and they do not seem to have been able to withstand the uneven load.

The salt domes or plugs are sometimes a few miles in width. Their salt has often forced its way through enormous depths of sediment, also measured in miles (Fig. 32). The salt of Persia is of Cambrian date, that is it belongs to the earliest fossiliferous formation. It carries great broken blocks of shale containing Cambrian fossils, and it lifts these with itself vertically through several miles of later formations.

When the Persian salt arrives at the surface it continues to well up like a slow-motion fountain, and spreads over surrounding modern deposits as a sheet known as a salt glacier (Fig. 33). Wherever it goes it carries blocks of rock along with it, showing that it has behaved like glacier ice.

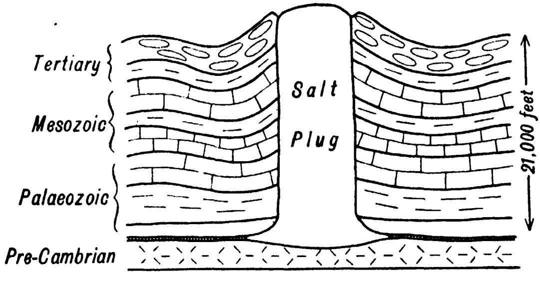

FIG. 32. Salt plug. (J. V. Harrison, *Inst. Petroleum Tech.*, 1931.)

It is only in, or near, Persia that salt glaciers are known. Elsewhere, when the salt arrives at the zone of circulating sub-surface water, the sodium chloride dissolves leaving a layer of anhydrite, $CaSO_4$, as cap-rock.

Salt domes are mainly valuable for the influence they have upon the migration of oil in adjacent strata, and for the sulphur which this oil sometimes produces through reactions with cap-rock.

We have already seen how oil tends to migrate into anticlines and domes. The domes raised by salt have proved to be among the most important oil reservoirs known to geologists.

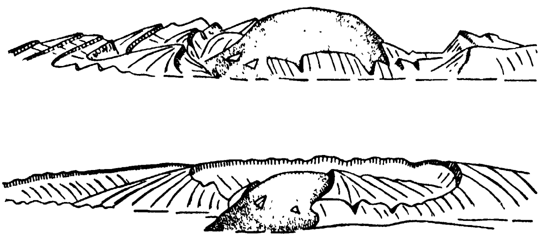

FIG. 33. Salt domes and salt glaciers. (Lees, *Inst. Petroleum Tech.*, 1931.)

The reaction producing sulphur is not wholly understood, but roughly it may be represented by the following equation :

$$CaSO_4 + C + 2H = CaCO_3 + H_2O + S.$$

Most of the sulphur of commerce comes from salt domes near the Gulf of Mexico. One dome alone has yielded £30,000,000 worth of sulphur. It is extracted by pumping down superheated water, which returns accompanied by molten sulphur.

CHAPTER XVI

GEOPHYSICAL SURVEY

SALT domes may be hidden under modern deposits, so as to make little or no show at the surface. The big money prizes that sometimes attach to their discovery have done much to inspire extremely ingenious and successful methods of prospecting, of a type called geophysical surveying. These methods naturally have many other applications.

(1) GRAVITATIONAL.—If a salt dome has a cap-rock of anhydrite, the high specific gravity of this mineral may lead to detection. The ground is surveyed with an extraordinarily refined balance, called the Eötvös balance, after its designer, an Austrian physicist. This balance will show any difference in the strength of gravity at its two ends. Thus, placed crosswise near the edge of a hidden anhydrite cap, the balance registers a minute difference of gravity that may be diagnostic.

The same method is also employed to help locate concealed masses of iron ore, or concealed anticlines or synclines, where these folds have cores of relatively heavy, or light, formations. The process is one of groping, with higher mathematics and physics, for a gravitational phenomenon that in turn must be interpreted in the light of the geological possibilities of the district. The answer is generally a well-founded guess that may assist enormously in the ultimate exploration by boring.

(2) EARTHQUAKE.—It is possible to produce artificial earthquakes by exploding charges of dynamite. It is also possible to obtain a time record of the arrival of the earthquake at any particular point. This gives the velocity with which the earthquake has been transmitted. The velocity of an earthquake depends upon the material which it traverses, and it happens that rock salt transmits earthquakes more rapidly than the sedimentary rocks with which it is generally associated. Thus velocity records may reveal the position of a concealed salt dome.

The gravitational method, mentioned above, requires elaborate observations concentrated within the critical area. This is apt to attract attention and raise land values—a distinct disadvantage from an Oil Company's point of view. The earthquake method escapes this difficulty, for the whole district is evenly investigated from a preconcerted net-work of stations.

Thus during the progress of the survey no one has grounds for guessing whether or no salt has been located, except the computator.

The earthquake method has numerous other applications. For instance, an earthquake passing down through relatively unconsolidated formations to a relatively consolidated floor tends to be reflected at the plane of contact. By taking the time of the echo an estimate may be formed of the depth of the contact. This may be an important matter for both science and economics.

(3) MAGNETIC.—It is easy to understand that a magnetic survey may furnish evidence of a relatively magnetic body, such as a mass of magnetite ore. It is almost as easy to realise that a magnetic survey may point to the position of an unusually non-magnetic body, such as a salt dome. Of recent years magnetic survey has achieved a great triumph in the indirect location of the famous Rand banket reef (a gold-bearing quartzite), where this formation is prevented from reaching the surface by an unconformable cover of dolomite. Elsewhere, at an exposed outcrop, the banket reef is found to be underlain at some distance down by three beds with marked magnetic properties. The sub-dolomite ' outcrops ' of these beds were sought and found by magnetic survey, and from their spacing it was possible to estimate the position of the banket. Boring then brought fortunes to those who had faith in the scientific guesswork of the expert in charge.

(4) ELECTRIC.—Conductivity experiments, based upon the high conductivity of wet rocks compared with dry, or of ores compared with silicates, have often led to valuable conclusions. The latest application is to test the conductivity, foot by foot, of bore holes put down for oil. The results after expert interpretation guide the operators to the levels at which oil is entering, levels at which the subsequent lining of the well should be perforated.

Other electrical prospecting seeks natural electric currents that may betray underground oxidation of sulphidic ores.

(5) AIR PHOTOS.—Though not usually included in the geophysical category, photography from aeroplanes may be mentioned as a modern aid to geological prospecting. Valuable results have been obtained in detecting ill-expressed salt domes in marsh-land, where a very small difference of elevation may lead to a pronounced difference in vegetation. Similarly air photos have helped in Africa through locating bare patches that mark exposures of copper ore.

(6) DOWSING.—Dowsers armed with hazel twigs claim to be able to detect underground water, rock contacts, etc. The practice is of old standing; but many scientists think that it is based, sometimes upon fraud, sometimes upon self-deception. A few good scientists believe that they possess the dowsing faculty. Our knowledge is at present in an unsatisfactory condition.

CHAPTER XVII

IGNEOUS ROCKS (PRINCIPLES OF CLASSIFICATION)

In introducing the great class of igneous rocks, emphasis was laid on the distinction between lava and intrusion (Chapter III). Let us add a definition of volcanic ash.

Volcanic ash is a rock produced by hot explosions. The adjective volcanic, as applied to rocks in strict geological speech, refers only to lava or ash. Intrusions are not volcanic, except in so far as volcanic ash may sometimes be described as intrusive, where, for instance, it is retained in the pipe of a volcano. The material blocking the pipe of a volcano, whether solid or fragmental, is said to occupy, or constitute, a neck, or, sometimes, a vent. Scotland is famous for its volcanic necks. Dumbarton Rock is a basalt neck. Dumgoyn, another conspicuous landmark in the neighbourhood of Glasgow, is an ash neck (Figs. 34, 35).

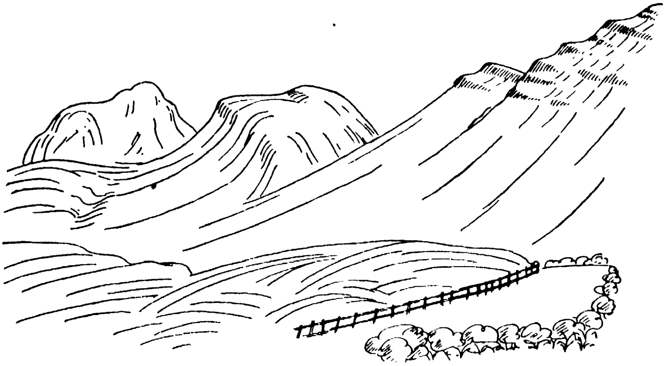

FIG. 34. Dumgoyn and Dumfoyn, Stirlingshire, from the south. Two volcanic necks of Lower Carboniferous age. Lavas of the same age on the right. Smooth slopes below lavas composed of Ballagan Beds on Upper Old Red Sandstone. (A. Geikie, 1897.)

Intrusions are split up for convenience into two great groups on the basis of size.

Where intrusions are of little individual thickness they are called minor intrusions or, less happily, hypabyssal intrusions ; *hypa* is used to mean subordinate, and *abyssal* suggests depth.

Where intrusions are big in all their measurements they are called major intrusions or plutonic intrusions. Pluto is invoked to recall the under world.

The adjectives volcanic, hypabyssal and plutonic are constantly used in Geology ; and it is well to understand that they have a slightly different scope when applied to rocks on the one hand and to rock-types on the other.

A volcanic rock is a lava or ash.

A volcanic type (*cf.* C in Figs. 37, 38), commonly occurs as a volcanic rock ; but it also may occur as a small minor intrusion. For example basalt, which makes most of the lavas of the world, also occurs as thin dykes and sills, which of course are typical forms of minor intrusions.

A hypabyssal rock is a minor intrusion.

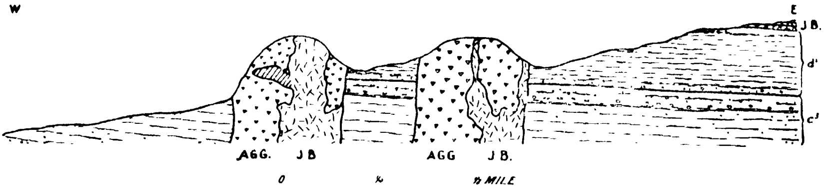

FIG. 35. Section through Dumgoyn and Dumfoyn necks. Agg., Agglomerate ; J.B., Jedburgh type of basalt occurring intrusive in the necks and as lavas on d′, Ballagan Beds, on c³, Upper Old Red Sandstone. (After Geol. Surv.)

A hypabyssal type (*cf.* B in Figs. 37, 38), commonly occurs as a minor intrusion ; but it may also occur as a big lava or a small major intrusion. Example : dolerite.

A plutonic rock is a major intrusion.

A plutonic type (*cf.* A in Figs. 37, 38), commonly occurs as a major intrusion, but it may also occur as an unusually large minor intrusion. Example : gabbro.

Thus, while volcanic, hypabyssal and plutonic rocks are distinguished by their relations determined in the field, volcanic, hypabyssal and plutonic types are distinguished by their characters determined by inspection of specimens, with either naked eye, lens or microscope. The criteria employed for the purpose are summed up under the heading texture.

Texture denotes the intimate mutual relations of the mineral constituents and glassy matter in a rock.

Volcanic types have textures characteristic of rapid cooling, that is they contain a considerable proportion of glass or very small crystals ; in other words the texture of much of their material is either glassy or microcrystalline.

Hypabyssal types have little or no glass, that is they are typically holocrystalline, a word which, in spite of its spelling, means wholly crystalline.

The general size of crystals is greater than that common in lavas, and smaller than that common in plutonic rocks. If augite and plagioclase occur together, there is a strong tendency for the augite to fit into the interspaces between the felspar laths, giving a texture known as ophitic (the pattern is supposed to recall the skin of an *ophis*, Latin for snake). If quartz and orthoclase occur together, there is a strong tendency for very minute and complicated intergrowth known as micrographic texture (where graphic conveys the idea of writing of the cuneiform type, Fig. 36).

FIG. 36. Granophyre, consisting of micrographic intergrowth of quartz (clear) and orthoclase (cloudy) as seen in thin section under the microscope (*see* Chapter XXVII).

Plutonic types are all holocrystalline ; and the grain size is considerable, so that individual crystals can easily be seen with the naked eye. Very often the crystal grains have so interfered with one another's growth that they do not exhibit their natural crystal faces, that is they are allotriomorphic (*allotrio* means strange, and *morphic* refers to shape, *cf.* amorphous).

In some specimens the distinction between volcanic, hypabyssal and plutonic types is very clear. In what we call the non-porphyritic varieties :

(1) Volcanic types are either glassy or crystalline of texture so fine as almost to escape the naked eye. The natural glass, obsidian, and non-porphyritic basalt are good illustrations.

(2) Hypabyssal types are sufficiently crystalline to show the texture clearly to the naked eye, but the different minerals are not very distinct. Thus a dolerite, consisting of black augite and white felspar, looks dark grey rather than black and white.

(3) Plutonic types are so coarsely crystalline that the different minerals occur as easily recognisable individuals. Thus a gabbro, consisting of the same minerals as dolerite is black and white.

On the other hand many specimens show a mixture of textures that at first sight is confusing. Some, that are labelled basalt, glitter with big crystals, as obvious as any in an ordinary gabbro (*cf.* the olivine and augite of Fig. 37C). Closer examination shows in such cases that the big crystals are enclosed in a fine-textured groundmass. This compound texture is called porphyritic and may be defined as follows :

In porphyritic texture large crystals called phenocrysts are set in a finer-grained groundmass.

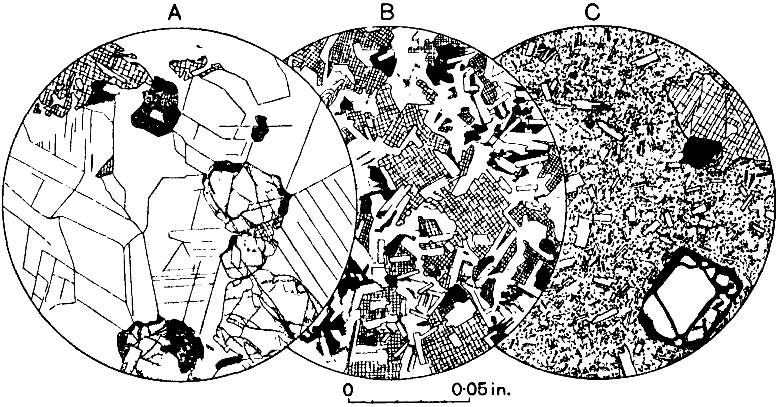

FIG. 37. A. Gabbro ; B. Dolerite ; C. Basalt. As seen in thin section under the microscope (*see* Chapter XXVII). Scheme of ornament : black and dark, iron ore and serpentine ; dotted, olivine ; checked, augite ; clear with indications of cleavage, felspar.

(The original porphyry of the Ancients was purple in colour, hence the name. *Pheno* comes from a Greek verb meaning to appear, *cf.* phenomenon.)

Porphyritic texture generally results from a change in the conditions of crystallization. Suppose a magma to be cooling slowly under plutonic conditions, its early crystals will grow with plutonic dimensions. Suppose now the magma rises from the deep-seated reservoir and is extruded as a lava, the residual melt, in which the early crystals are enveloped, may consolidate as glass or as a microcrystalline aggregate. This is the history of the porphyritic texture of many lavas. The change of conditions responsible for porphyritic texture is not always as extreme as outlined above. After a check the residual melt may continue to crystallise under hypabyssal or plutonic conditions. A porphyritic rock is classed as of volcanic, hypabyssal or plutonic type according to the texture of the groundmass. Plutonic types are represented by porphyritic granite at Glen Fyne, Shap, Cornwall and elsewhere. On the whole, however, porphyritic texture is commoner among volcanic and hypabyssal types.

A division of igneous types according to texture is not sufficient in itself, for there is a very wide range of variation in chemical and mineralogical composition, and this must be taken into account. Igneous rocks, viewed chemically, are almost wholly made of silicates, accompanied in certain cases by free silica. These components differ very greatly in composition, but they can be grouped roughly according to the proportion of silica (SiO_2) which they yield on analysis. The following table is useful :

Quartz		Pure SiO_2
Acid felspars	Orthoclase Albite	Rich in SiO_2
Intermediate felspars	Oligoclase Andesine	Moderate in SiO_2
Basic felspars	Labradorite Bytownite	Poor in SiO_2
Hornblende		
Augite		
Ultrabasic felspar	Anorthite	Very poor in SiO_2
Biotite		
Olivine		

Orthoclase and albite are called acid felspars, because on analysis they give a high percentage of the acidic oxide SiO_2. At the same time they are the felspars of K and Na, which are called the alkali metals. So we have the curious fact that the extreme acid felspars are equally often called the alkali felspars.

The basic and ultrabasic felspars are those plagioclase felspars that are rich in Ca.

Once we realise something about the chemical composition of minerals, we can form a good idea about the chemical composition of rocks made of these minerals. On examination a granite is seen to consist largely of quartz and orthoclase. Obviously granite must on analysis contain a high percentage of silica : it is what geologists call an acid rock.

On the other hand gabbro consists of basic felspar and augite, with very often olivine too : the rock itself must be basic.

More generally : as the ferromagnesian minerals are all basic or ultrabasic, a dark igneous rock is probably either basic or ultrabasic.

There are further points which emerge. A granite rich in orthoclase evidently has resulted from a magma rich in K. If it contains a ferromagnesian silicate, we should expect this also to contain K. Now the only igneous ferromagnesian silicate containing K is biotite ; therefore we are not surprised to find that biotite is the most characteristic ferromagnesian mineral of granite, although biotite is more basic than either hornblende or augite.

The two minerals hornblende and augite have rather closely comparable compositions. They are both ferromagnesian minerals containing Ca; but hornblende tends to be poorer in Ca and at the same time richer in Na, which explains its common association with the intermediate felspars. No mention has previously been made in these pages of Na in connection with hornblende, because it is a very minor constituent. It is, however, significant in the present connection; so that it is useful to think of biotite as the K-ferromagnesian silicate, and of hornblende as the Na-ferromagnesian silicate.

After this introduction we may lay down the SiO_2 boundaries adopted in the chemical classification of igneous rocks:

Ultrabasic	35–45 per cent. SiO_2
Basic	45–55 per cent. SiO_2
Intermediate $\left\{\begin{matrix} Ca - Na \\ Na - K \end{matrix}\right\}$	55–65 per cent. SiO_2
Acid	65–75 per cent. SiO_2

It will be seen that two branches are recognised in the Intermediate class; the one is rich in plagioclase felspar, the other in orthoclase.

CHAPTER XVIII

IGNEOUS ROCKS (CLASSIFIED)

IN the explanation of the Table (p. 90) it is pointed out that Basalt and Granite are both doubly underlined, because of their extreme abundance. Basalt is the commonest of lavas. This is probably in part due to the great fluidity of basic magma. A modern basalt lava has been known to flow for forty miles after reaching the surface. Granite is the commonest of intrusions. This is probably in part due to the stickiness of acid magma under superficial conditions. Very often acid igneous rocks only reach the surface as fragments carried up by volcanic explosions.

The definitions that follow repeat the information summarised in the Table, and are made the basis of appropriate discussions.

GRANITE (Fig. 38A)

Composition : 65–75 per cent. SiO_2.

Minerals : Orthoclase, quartz, biotite.

Texture : Coarse holocrystalline ; allotriomorphic or hypidiomorphic.

The terms holocrystalline and allotriomorphic have already been explained. Hypidiomorphic means that individual crystals show a tendency to idiomorphism or proper form (*idio* means belonging to oneself, *cf.* idiosyncrasy, some would say, *cf.* idiot).

The minerals given in the Table are the more important minerals, often called the essential minerals. They are accompanied by small quantities of other minerals called accessory minerals. Magnetite and apatite are found as accessories in almost any type of igneous rock.

Igneous rocks are, to use a chemical phrase, mixtures not compounds. There is therefore no sharp line separating adjacent types. For instance, every gradation connects granite with syenite and quartz-diorite. Thus hornblende and plagioclase often appear in rocks which are quite properly included as granite. A granite containing hornblende may be called a hornblende-granite, without troubling to invent a new name.

The granites of different districts can often be distinguished. Thus muscovite accompanies biotite in the granites of Cornwall and Devon, but is very seldom found in the granites of Western Scotland. Granite is by far the most voluminous intrusive type in the Highlands and Southern Uplands of Scotland, and, of quite a different date, in Cornwall and Devon.

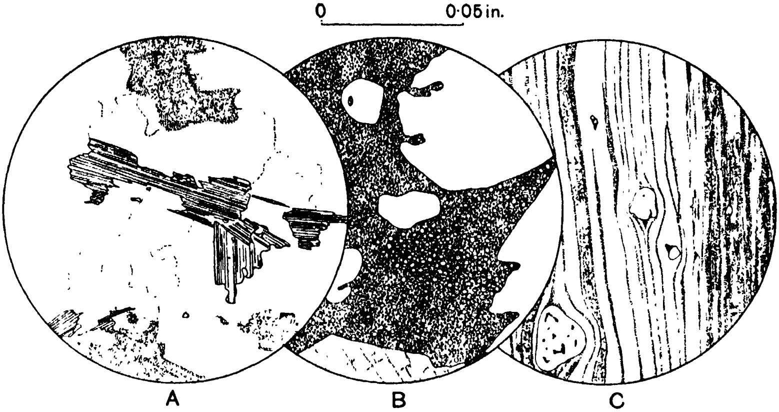

FIG. 38. A. Granite, with clear quartz, cloudy felspar and cleaved biotite ; B. Quartz-felspar-porphyry ; C. Rhyolite, with flow structure. As seen in thin section under the microscope (*see* Chapter XXVII).

PORPHYRY AND FELSITE (Fig. 38B)

Composition and *Minerals* : same as in granite.

Texture : holocrystalline, but to some extent micro- or even cryptocrystalline (*crypto* means concealed, *cf.* crypt). Micrographic intergrowth of quartz and orthoclase is very frequent. So too are spherulites of orthoclase, in which radiating bundles of orthoclase, often associated with quartz, grow from individual centres to build little spheres. Porphyrics are distinguished from felsites by possessing porphyritic texture. According to general English custom the phenocrysts of a porphyry include either quartz or alkali felspar, or both.

RHYOLITE AND OBSIDIAN (Fig. 38C)

Composition and *Minerals* : same as in granite with the addition of glass.

Texture : cryptocrystalline in rhyolite to glassy in obsidian. Either type may be porphyritic. Spherulitic structure and flow banding are very frequent.

FIG. 39. Perlitic cracks in glass as seen in thin section under the microscope (*see* Chapter XXVII).

Glassy rocks often develop small systems of concentric spherical cracks, known as perlitic cracks, as a result of shrinkage during cooling (Fig. 39).

IGNEOUS ROCK TYPES FOR FIRST YEAR STUDENTS

Silica Percentage	ULTRABASIC 35–45	BASIC 45–55	INTERMEDIATE 55–65		ACID 65–75
			Ca – Na	Na – K	
Characteristic Minerals	Olivine				
	Augite				
			Hornblende		
			Biotite		
		Plagioclase			
				Orthoclase	
			Some Quartz		Quartz
VOLCANIC	Oceanite	Basalt	Andesite	Trachyte	Rhyolite and Obsidian
HYPABYSSAL	Peridotite	Dolerite and Lamprophyre *	Porphyrite	Trachyte	Felsite and Porphyry
PLUTONIC	Peridotite	Gabbro	Quartz-Diorite	Syenite	Granite

* Lamprophyre is *basic*, with a strong concentration of ferromagnesian minerals, but its mineral species are characteristically those listed under the *intermediate* heading.

The limits given for Characteristic Minerals are only convenient approximations. Thus Plagioclase is specially characteristic of Basic and Lime-Soda-Intermediate Rock-Types, but it also occurs in many Soda-Potash-Intermediate and Acid Rock-Types.

The double underlining of Basalt and Granite draws attention to the extreme abundance of these Rock-Types. Dolerite, Lamprophyre, Andesite, Porphyrite, Quartz-Diorite, Felsite and Porphyry are also abundant.

ADDITIONAL TYPES NOT LISTED IN THE TABLE

Two additional rather special types may be added, which are of importance in the West of Scotland:

(1) Pitchstone is a hydrous volcanic glass with resinous lustre. It is called pitchstone because it looks like pitch, not because it is made of pitch. There are both intermediate and acid pitchstones. The pitchstone of the Scuir of Eigg is a lava. The pitchstones of Arran are small intrusions.

(2) Granophyre is a rock of granitic composition, distinguished by micrographic intergrowth of quartz and orthoclase (Fig. 36). The coarser varieties are plutonic, and typically exhibit drusy cavities into which neighbouring crystals project with well-formed faces; these cavities were filled with superheated water-solutions at the time the crystals grew. The finer varieties often carry spherulites, and are hypabyssal, grading into porphyries and felsites. Granophyres are commonly found associated with gabbros, as in Skye and Mull.

Two widespread rock-types occur on a small scale as relatively acid segregation veins associated with plutonic, and to a less extent hypabyssal, rocks:

(3) The coarser type is called pegmatite. Granite-pegmatite is rich in quartz and orthoclase. It often shows graphic intergrowths, but this is not considered essential in the definition of the type. Pegmatites frequently contain rare and valuable minerals. Many pegmatites occur at a distance from plutonic masses, and may even result from hydrous melts that have developed during metamorphism.

(4) Aplite is distinguished from pegmatite by its very fine texture. It is typically microgranular, without graphic intergrowths. Granite-aplite is a variety of felsite.

Rhyolite is rather common in Wales, where Snowdon is made of rhyolitic ash. Rhyolite lavas make the finest scenery of Glen Coe.

SYENITE

Composition : 55–65 per cent. SiO_2, coupled with richness in K and Na.

Minerals : orthoclase, biotite, hornblende.

Texture : coarse holocrystalline ; allotriomorphic or hypidiomorphic.

Syenite is a rare type compared with granite. It often contains some quartz and plagioclase felspar, thus showing relationship to granite and quartz-diorite. Quartz-free syenites usually include rather rare minerals, among which the most important is nepheline.

Nepheline is a silicate of Al and Na, with a smaller percentage of SiO_2 than in albite. It is of the hexagonal system.

Nepheline is called a felspathoid to remind us that it is related in composition to the Na-felspar, albite. There is a corresponding Al-K-felspathoid related to orthoclase. It is called leucite, and crystallizes in the cubic system. It is never found unaltered in plutonic rocks, because on slow cooling it decomposes. It is, however, well known in lavas. The lavas of Vesuvius are leucite-bearing basalts.

Syenites with felspathoids are called alkali syenites.

Though the leucite of plutonic rocks always decomposes during cooling, its former presence can sometimes be recognised, where aggregates of secondary minerals preserve its characteristic shape. This illustrates a common phenomenon in igneous rocks. Very often a primary mineral is replaced by one or more secondary minerals which preserve the form of the primary mineral. In such a case the secondary minerals are said to constitute a pseudomorph after the primary mineral.

Pseudo suggests falsity, and here advertises the fact that the secondary minerals are displaying a *morph*, or shape, that is not their own.

Syenites occur near Loch Assynt in Sutherland.

TRACHYTE

Composition and *Minerals* : same as in syenite. Glass is very unimportant.

Texture : medium to fine holocrystalline, panidiomorphic (*pan* means all, *cf.* pan-American). The dominant mineral in trachyte is orthoclase, generally in the form of laths, arranged in parallelism by flow. The resultant texture is known as trachytic. Trachytes may be either porphyritic or non-porphyritic.

It will be noted that the name trachyte is used for both volcanic and hypabyssal types. It might be convenient to have different names for fine-grained and medium-grained trachytes ; but the type is comparatively rare, and most people agree that one name will do.

Trachytes with felspathoids are called phonolites, because they give a musical ring under the hammer, and *phonos* means voice. Traprain Law and the Bass Rock, two well-known Scottish landmarks, are intrusions of nepheline-phonolite.

QUARTZ-DIORITE

Composition : 55–65 per cent. SiO_2, coupled with richness in Ca and Na.

Minerals : plagioclase, biotite, hornblende, with subordinate quartz.

Texture : coarse holocrystalline ; allotriomorphic or hypidiomorphic.

The plagioclase felspars of quartz-diorites are usually oligoclase and andesine. Hypersthene is a common ferromagnesian mineral in some varieties. It belongs to a mineral family known as pyroxene, which also includes augite. Hypersthene differs from augite in its crystal system, which is orthorhombic. Thus hypersthene is called an orthorhombic pyroxene, and augite a monoclinic pyroxene. When we come to consider the optical properties of minerals, we shall find that orthorhombic and monoclinic minerals are easily distinguished.

Quartz-diorites are common in the Highlands and Southern Uplands of Scotland.

PORPHYRITE

Composition and *Minerals* : same as in quartz-diorite.

Texture : porphyritic with medium-grained holocrystalline groundmass, generally containing micrographic intergrowths of quartz and orthoclase. It is essential, according to usual English standards, that plagioclase, more basic than albite, should occur among the phenocrysts. These latter generally also include biotite or hornblende. There are very many porphyrite dykes in the Highlands and Southern Uplands of Scotland.

ANDESITE

Composition and *Minerals* : same as in quartz-diorite, except that quartz is generally absent and glass generally present.

Texture : usually porphyritic with plagioclase and ferromagnesian pheno crysts in a fine-grained groundmass, which may be either glassy, hyalopilitic or pilotaxitic.

Hyalopilitic denotes a felt-like web of minute plagioclase laths, with glass between—*hyalo* is the Greek for glassy; *pilum* is the Latin for dart and refers to the microscopic appearance of the plagioclase laths. This type of groundmass is so characteristic of andesites, that it is often called andesitic.

Pilotaxitic denotes a similar groundmass, except that it is almost free of glass. *Taxitic* is from a Greek word meaning arrangement.

Andesine is a very characteristic felspar in andesites. The mineral and rock both take their names from the Andes in America, which are largely built of andesite lavas and ashes. In fact all the great ring of volcanoes that girdles the Pacific from America to Japan produces andesite as its commonest type. The lavas of Ben Nevis, and many of the lavas of Glen Coe, are andesite. Andesite lavas and ashes are also strongly represented in the Lake District.

GABBRO (*cf.* Fig. 37A)

Composition : 45–55 per cent. SiO_2.

Minerals : labradorite, augite and often olivine.

Texture : coarse holocrystalline ; allotriomorphic or hypidiomorphic.

The labradorite and augite of gabbro often carry innumerable minute inclusions, geometrically arranged. These are spoken of as schiller inclusions, because of the iridescent reflections which they give. The augite of gabbro may also exhibit an additional cleavage and is then called diallage.

Gabbro though fairly rare makes the Cuillins of Skye, and on a larger scale a great mountain zone in Southern Norway.

DOLERITE (Fig. 37B)

Composition and *Minerals*: same as in gabbro but without schiller inclusions or diallagic cleavage.

Texture : medium, holocrystalline, very often ophitic.

Dolerite is the commonest intrusive type of the Midland Valley of Scotland and of the North-East of England. It is found in Edinburgh at Salisbury Crags, and in Glasgow at the Necropolis Hill and Fossil Grove. What may be a single sill carries Stirling Castle, the Forth Bridge at Queensferry and long stretches of the Roman Wall in Northumberland (the Great Whin Sill of the North of England).

Where dolerite intrudes into carbonaceous sediments it distils gas from these sediments, and during the process of cooling it is attacked by the gases it has itself made. Thus its silicates are largely converted to kaolin and dolomite, and the resultant rock is known as white trap. White trap is very common in Scotland, and is typically developed at the Fossil Grove.

LAMPROPHYRE

Composition : same SiO_2 limits as in gabbro.

Minerals : same as in syenite or quartz-diorite.

Texture : medium holocrystalline, panidiomorphic, porphyritic with phenocrysts of ferromagnesian silicates only.

Mineralogically the lamprophyres correspond more closely with syenite and quartz-diorite than with gabbro. They often contain orthoclase, and plagioclase felspars that are more acid than labradorite, along with biotite and hornblende. It is the concentration of these two ferromagnesian minerals that leads to lamprophyres being basic instead of intermediate.

Lamprophyres accompany the porphyrites of Scotland.

BASALT (Fig. 37c)

Composition and *Minerals* as in gabbro, with sometimes a little glass.

Texture: fine-grained; porphyritic or non-porphyritic; the augite either microophitic, microgranular or microprismatic.

Basalt is the commonest lava type in the world. Examples: Iceland, Columbia River (U.S.A.), Deccan (India), Antrim (Ireland), Skye and Mull (Hebrides), Campsie Fells and Kilpatrick Hills (Glasgow).

PERIDOTITE, fr quently altered to SERPENTINE (Fig. 40A)

Composition: 35–45 per cent. SiO_2.

Minerals: olivine, augite and sometimes anorthite.

Texture: coarse to medium holocrystalline; allotriomorphic or hypidiomorphic.

The peridotites are rather rare, and it has not been thought necessary to have separate names for the hypabyssal and plutonic types.

Fresh peridotites occur in Rum, and serpentines in Ayrshire and at the Lizard in Cornwall.

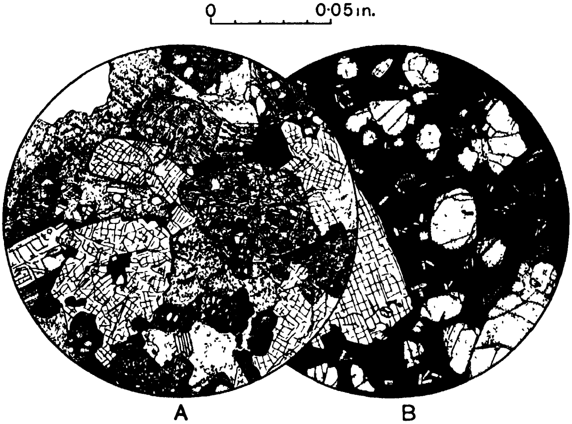

FIG. 40. A. Peridotite; B. Oceanite. As seen in thin section under the microscope (*see* Chapter XXVII). Ornament scheme: dotted, olivine; close-lined, serpentine after olivine; checked, augite; clouded, plagioclase unusually abundant; opaque base of B contains much glass, iron ore, etc.

OCEANITE (Fig. 40B)

Composition and *Minerals* : same as in peridotite.

Texture : fine-grained holocrystalline, seldom glassy.

A number of names are current for various types of ultrabasic volcanic types. Oceanite is rich in olivine. The name is connected with the relative abundance of ultrabasic lavas in oceanic islands.

The frequency of basic and ultrabasic rocks in oceanic islands, coupled with gravity determinations that indicate a high density for ocean beds, suggests that deeply submerged areas are floored with basic and ultrabasic rocks. This is in keeping with the world-wide association of basic and ultrabasic igneous rocks with radiolarian chert, which is interpreted by many as an upheaved oceanic deposit. Deep-sea lavas and intrusions are usually much altered with development of albite, epidote, chlorite and serpentine. Their alteration is probably due to interaction with sea water under pressure. It recalls to some extent the production of white trap in a carbonaceous environment. Decomposed basic submarine lavas are often called spilites.

The continents, in contrast to the ocean beds, are largely made of relatively siliceous material that floats upon a basic substratum, continuous, it is supposed, with that which floors the oceans.

CHAPTER XIX

EVOLUTION OF ROCKS

THERE is no doubt that sediments have derived their material from igneous rocks, with additions from the sea and atmosphere. It is true that the derivation may be at second or third hand. A sandstone very often has got its quartz from an older sandstone, unmetamorphosed or metamorphosed, but the original sandstone of the series must have got its quartz from some igneous rock, generally a granite, or, to a very minor extent, from quartz veins, etc. Logically therefore it would be preferable to start a discussion of the evolution of rocks with a discussion of the evolution of igneous rocks. On the other hand the processes involved in the production of sediments are so commonplace and familiar that it seems justifiable to begin with sediments.

SEDIMENTS

In the production of sediments we must first take account of two preparatory processes :

(1) fragmentation ;
(2) chemical decomposition.

These may act, either singly, or together. We shall return to them in later chapters.

After the material has been prepared it is subjected to sorting processes :

(1) current action, which leads to deposition of conglomerate, sandstone and shale in different belts ;
(2) solution, which preferentially removes Ca and Na from mechanical sediments, and preferentially spares Al and SiO_2 ;
(3) organic precipitation, which leads to formations rich in $CaCO_3$, SiO_2 or C ;
(4) evaporation, which leads to formations rich in $CaSO_4 . 2H_2O$, NaCl, etc.

Let us for a moment consider the chemistry of the operations.

A conglomerate, if it has originated from the fragmentation and transport of uniform material, may retain the chemical characteristics of its source unaltered.

A typical sandstone consists mainly of quartz. Such a sandstone usually results directly, or indirectly, from destruction of granite. The quartz grains of granite are big enough to be seen with the naked eye, and, being hard and insoluble, they tend to retain much of their original dimensions. Current action sorts them out in a belt between pebbles, on the one side, and mud, on the other. The composition of many sandstones approaches pure SiO_2. This may result from a splitting up of granite without addition from any external source.

A typical mud may be developed by chemical decomposition of igneous rocks, followed by sorting through current action and solution. Current action, as already explained, tends to segregate quartz as sand, while solution tends to remove Ca and Na and to spare Al. During decomposition of igneous rocks hydrated minerals are formed, either silicates or oxides. Some of these easily break down to an incoherent powder of microscopic or submicroscopic grain. When such powder is washed into rivers, it can only rest on a bottom that is free from current: for instance, within the Mud Belt of a lake or of the sea. Flaky minerals, such as muscovite and chlorite, even though of larger size, accompany the powder to the Mud Belt, because their shape makes them very susceptible to currents. The processes outlined above give mud a characteristic chemical composition : SiO_2, Ca and Na tend to be low ; Al tends to be high ; K, carried in muscovite, tends to be moderately high ; and there is always a considerable amount of combined H_2O, which cannot be removed by simple drying. Mud, unlike sand, cannot be regarded as entirely due to the splitting up of igneous rocks, for its combined water is an addition.

The chemistry of organic and chemical precipitation is too obvious to detain us. It will be noticed that it differs profoundly from that of igneous rocks. Thus in a limestone one finds Ca separated from its usual metal associates, and combined with CO_2 instead of SiO_2.

IGNEOUS ROCKS

Although igneous rocks at the present time have a very wide range of chemical composition, to begin with they were presumably represented by a single silicate magma of fairly uniform composition and of world-wide extent. This covered a metallic core, consisting mostly of iron and only very slightly soluble in the overlying silicate melt. The original uniformity of the primeval silicate magma is a laboratory deduction. If any two, three or more igneous rocks are melted together in a crucible, they mutually dissolve to give a single uniform solution.

To-day there are, as we have seen, very great chemical differences separating many of the familiar types of igneous rock. The processes concerned in bringing about these differences must be as methodical as those that bring about the differences between the various types of sediments, because granite and basalt, to confine our attention merely to the two commonest igneous types, are found in numberless places with chemical characteristics just as well defined as those of sandstone and shale.

The two processes which seem most important in developing an assemblage of rock types from a uniform magma are :

(1) CRYSTALLISATION, which prepares the way by dividing the material into two chemically dissimilar parts : early crystals and residual melt.

(2) SORTING, which separates the early crystals from the residual melt. Sorting may be done in a variety of ways :

(*a*) GRAVITATIONAL SORTING : if the early crystals sink, they automatically separate from the residual melt. Sinking is not nearly so potent in silicate melts as in water solutions, because of high viscosity. Thus consolidated lavas very seldom show any difference of composition all the way from top to bottom.

(*b*) DRAINING OR SQUEEZING of the residual melt from a meshwork of early crystals.

Both these sorting processes are effective in Nature.

(*a*) Gravitational sorting is illustrated in a dozen examples among the plutonic intrusions of Mull. The particular intrusions are individually about a quarter of a mile broad and are exposed in vertical depth on the hill sides for about 1,500 feet. The tops of their exposures are acid and relatively light and the bottoms basic and relatively heavy, with every intermediate stage between (Figs. 41, 42). This is to be expected in gravitational sorting, for it is found by experiment and observation that the early crystals from a silicate melt are more basic, and also specifically heavier, than the residual melt. Let us give the contrast between the top and bottom of one of these Mull exposures :

	Top	*Bottom*
Colour - -	pale pink	black and white
Spec. gravity -	2·5	3·0
Minerals - -	alkali felspar and quartz	labradorite and augite
SiO_2 per cent. -	68	50

(*b*) Sorting by squeezing out of residual melt is exemplified in the very prevalent formation of aplite veins during the crystallization of intrusions. These aplite veins represent the penultimate residual melt segregated from almost completely crystallized rock. They are particularly abundant in association with plutonic rocks, where they generally occur in the marginal zone a little inside, or a little outside, the plutonic mass. Their attitude in such a position may be anything from horizontal to vertical. More occasionally an aplite vein occurs in a flat dolerite sheet, in which case it presents a relatively simple geometry that helps us to interpret its origin. Such a vein

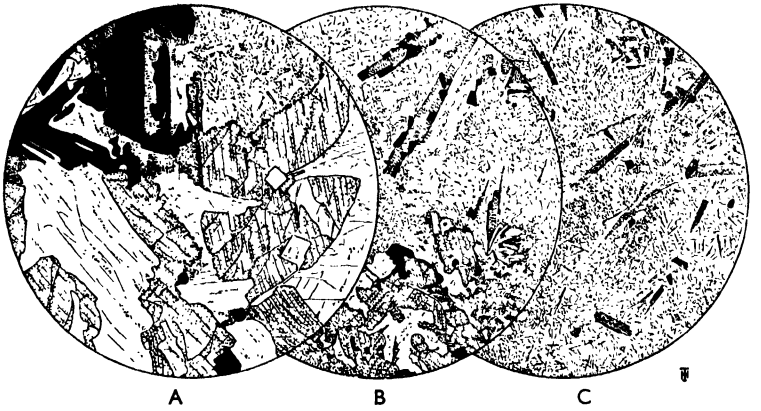

FIG. 41. Differentiation products, Glen More, Mull, as seen in thin section under the microscope (*see* Chapter XXVII).

A. Lower basic portion : gabbro ; black crystals, iron ore ; shaded grey, augite ; white, plagioclase ; note patch of fine-grained acid residuum at right top of section. (After Geol. Surv.)

B. Intermediate portion : largely acid residuum.

C. Higher acid portion : mostly acid residuum.

avoids the chilled top and bottom of its host, choosing instead the more crystalline central part, where it adopts a moderately flat posture. It commonly measures an inch or so in thickness. Obviously, when it was liquid, it must have been injected into a horizontal crack under a pressure

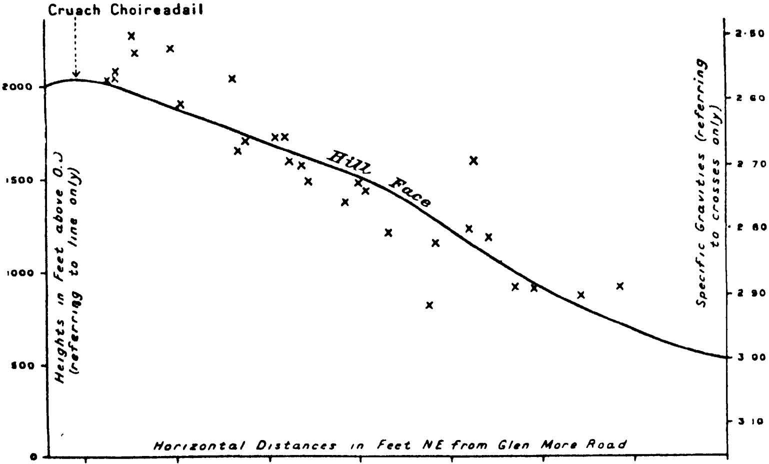

FIG. 42. Graph showing relation of specific gravity to altitude in gravitationally differentiated large-scale intrusion, Glen More, Mull. (After Geol. Surv.)

that was sufficient to raise the overlying mass of rock, including very probably some thousands of feet of sediment. The injection-pressure can only have been supplied by steam, the agent responsible for the terrific explosions that occur at volcanic centres. Silicate magma under pressure can dissolve a considerable amount of water. As the early crystals develop, this water is concentrated into the residual melt. With increasing concentration the pressure required to keep the steam in solution rises. Eventually when there remains very little residual melt, the concentration of water becomes so great that its vapour pressure exceeds the pressure due to the weight of the covering rock. Let us form a simplified picture of the sill at this stage. It has a completely solid top and bottom resulting from chilling against roof and floor. In between it is almost solid. We may regard it, for diagrammatic purposes, as consisting in this middle part of a series of irregular pillars of solid matter binding together the top and bottom (the shape of the pillars and interspaces is immaterial, but it is easier to visualise the mechanics if they are pictured approximately vertical as in Fig. 43). Between the columns is residual melt. When this melt is forced to liberate steam at a higher pressure than that which weighs upon the roof, it can only find relief upwards, by straining the pillars. If the pillars snap, some residual melt is forced by the steam into the resultant cracks, and furnishes the veins which we call aplite veins.

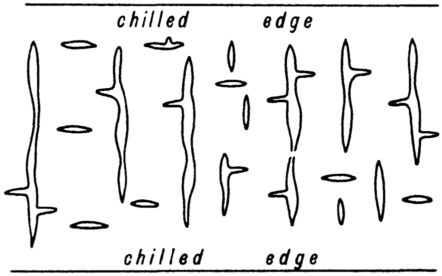

FIG. 43. Diagrammatic representation of the distribution of residual magma in an almost completely consolidated dolerite sill. In the next stage growing steam pressure develops a horizontal aplite vein in the middle of the sill.

It will be noticed that, according to this explanation, aplite veins do work against external pressure in forcing room for themselves. This furnishes a partial answer to a long-standing puzzle. Aplite veins are more finely crystalline than the rocks they traverse. They have a texture which suggests rapid cooling. This is exactly what would be expected if the veins have had to expend some of their energy in making room for themselves. They would cool themselves, much as a gas cools itself when it expands suddenly against external pressure. Calculations suggest that such a mechanical cooling would not be sufficiently important to account unaided for the observed effects. It is, however, possible to invoke the aid of contributory factors. The sudden relief of pressure, accompanying a snap, must allow an accumulation of water to pass into steam, which by changing the composition of the residual melt must leave it supersaturated, and by mechanically stirring it must favour rapid fine-textured crystallization.

The processes of crystallization and sorting that we have considered split up an original magma into two dissimilar parts. By sorting at intervals during the process of crystallization, many dissimilar parts may be obtained. By remelting the crystal crops, and repeating crystallization and sorting, the variety of the products can be increased. This is a method constantly employed in chemical laboratories and industrial works, where it is known as fractional crystallization.

The name differentiation has been given in Geology to the splitting up of an original magma, often called the parent magma, into a number of unlike parts. Differentiation is a subtractive phenomenon ; there is no addition of material from outside. It is the only phenomenon that concerns us when we contemplate the production of new types from a universal magma.

Once magma can come in contact with already differentiated igneous rocks, or with sediments, an additive phenomenon, assimilation, becomes possible. Assimilation may modify a magma through incorporation by solution of external material.

Field observations show that igneous magmas have often been modified by assimilation. The extent, to which assimilation is responsible for the large number of igneous types that we know, is a matter of dispute. Many think that assimilation plays only a minor rôle compared with differentiation. Certainly igneous rocks have *not* resulted from wholesale melting of sediments, without some process of admixture, for igneous rocks differ in chemical composition from sediments.

Let us take an illustration. Suppose we could not make chemical analyses, it might be suggested that granite has resulted from melted sandstone, and basalt from melted shale. Chemical analysis forbids any such theory. In a typical granite the SiO_2 percentage is lower, and the K_2O percentage higher, than in a typical sandstone. Similarly in a typical basalt, or any other basic igneous rock, the CaO percentage is higher than that of MgO, the Na_2O percentage is higher than that of K_2O, and the molecular sum of $CaO + Na_2O + K_2O$ is higher than the molecular value of Al_2O_3 ; whereas in a typical shale all these relations are reversed. It may be added that in the felspars, which are the commonest of igneous minerals, the molecular ratio of $CaO + Na_2O + K_2O : Al_2O_3$ is 1 : 1.

CHAPTER XX

JOINTS

BEFORE passing on to vein-stones it is important to know something more of the division planes that exist in rocks, since they often guide the deposition of subterranean precipitates.

We have already dealt with bedding planes. Now let us consider joints.

Joints are cracks in rocks, along which there has been little or no relative movement except separation on a minute scale.

All consolidated rocks are jointed. This is what might be expected. We have seen that the earth's crust is subject to movement, and it is inconceivable that great sheets of brittle material, such as are furnished by beds of consolidated rock, could be moved about without cracking. We shall see presently that shrinkage, due to one cause or another, is responsible for certain joints; but earth movement, of one sort or another, is responsible for the universality of the phenomenon.

There are usually three sets of joints, roughly at right angles to one another. In sediments one of these three sets generally approximately follows the bedding (Fig. 44).

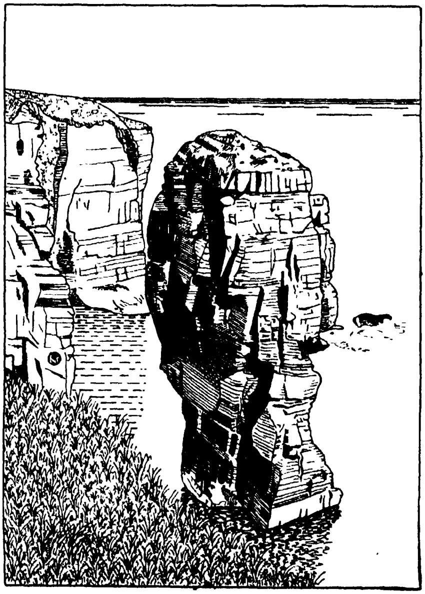

FIG. 44. Flagstone stack, Lybster, Caithness.

Note two sets of vertical joints at right angles to one another and to the bedding. (Geol. Surv. photo.)

Particularly prominent joints, which continue their course uninterruptedly for a considerable distance, are called master joints. One or two of the three sets of joints usually provide the master joints; the remaining set, or sets, consists of joints with interrupted course. Such interrupted joints stop, and start again, at master joints. They retain parallelism, though not continuity.

Igneous rocks are often jointed in a very characteristic manner, and it is obvious that such special jointing cannot be ascribed to earth movement. All agree that the columnar structure, frequently developed in lavas and minor intrusions, is cracking due to shrinkage of the rock during cooling after consolidation (Fig. 45). Columnar jointing is illustrated in many parts of the world, but no examples are more famous than those of the basalt lavas seen at the Giant's Causeway on the Antrim coast (Fig. 46), and at Fingal's Cave in Staffa.

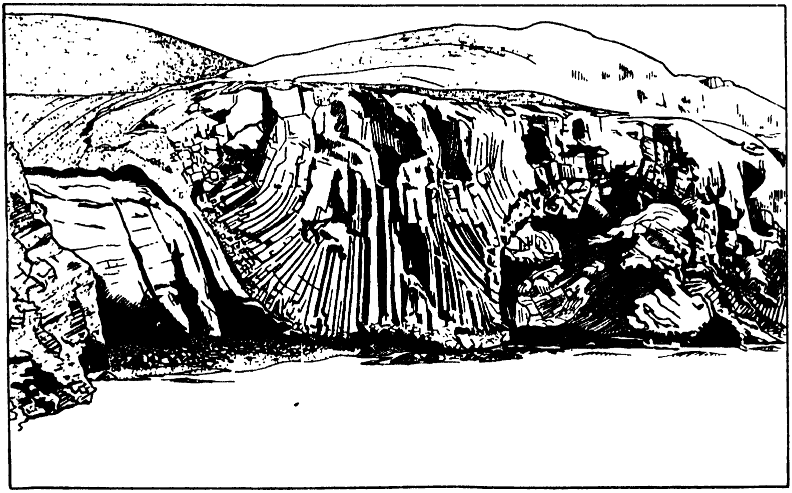

FIG. 45. Base of columnar basalt sheet, probably lava, on irregular surface of agglomerate, Frodebö, Faroes. (Nat. Geog. Mag. photo.)

Such shrinkage joints develop in the direction of cooling. This is a matter of observation, for in a horizontal intrusive sheet, which must have cooled from above and below, the joints are vertical; whereas in a vertical intrusive sheet, that is in a dyke, the joints are horizontal. We can picture the joints developing at some appropriate temperature of snapping, and keeping pace during their development with the advance of the isothermal surface corresponding to this particular temperature. The rock along this isothermal surface will tend to contract uniformly in all directions included in the surface. It satisfies this tendency by contracting not towards a single centre, which would involve comparatively large-scale movement, but towards a multitude of centres distributed as uniformly as is possible within the isothermal surface.

The most uniform distribution of centres imaginable corresponds with that belonging to rows of billiard balls packed as closely as may be. The balls fit into straight rows, with each successive row half a ball in front of, or, what is the same thing, half a ball behind, its predecessor. In this alternating arrangement each ball touches six other balls, so that each centre is equally close to six other centres, the greatest number attainable. The contraction of the material between each pair of adjacent centres will tend to produce a crack bisecting at right angles the line that joins the centres. Such cracks will obviously constitute regular hexagons, each hexagon enclosing a centre of contraction. In Nature regular columnar jointing shows a marked tendency to assume a hexagonal pattern.

Let us now return to the statement that joints grow in the direction of cooling. Sometimes a vertical intrusion is found with vertical columns, where at first sight horizontal columns might be expected. This happens, for instance, in the cylindrical plug of basalt that occupies the Dumbarton neck. We are justified in assuming in such a case that, by the time the intrusion had cooled to the temperature of jointing, the wall rocks had been sufficiently heated to make cooling from above more important than cooling from the side.

Often there is only one set of columnar joints developed in a lava or an intrusion ; but at the Giant's Causeway and Staffa we find basalt lavas that have developed two sets of columnar joints. In each case there are broad regular columns in the lower part of the lava, which are due to slow regular cooling from the base ; while there are narrow irregular columns in the upper part, which are due to rapid irregular cooling from the top. This compound type of jointing is called double-tier jointing. Fingal's Cave has been quarried by the waves in the lower regular tier, leaving a roof supplied by the upper irregular tier, in which the tendency for an undermined column to fall is greatly reduced.

FIG. 46. Columnar jointing, Giant's Causeway, Antrim. (J. R. Shelford photo.)

Those of you who know the great road-metal quarry at Troon, in Ayrshire, with its big export trade to England, must have admired the perfect vertical columns of the quarried dolerite. The quarry was selected for large-scale development because of the jointing. A single blast at the base of a column may bring the whole to the floor.

Shrinkage cracks due to drying are responsible for some of the jointing of sediments. Columnar jointing of peaty mud is a very familiar sight during dry weather in the Highlands. Drying mud, on what has been the flat bottom of a peaty pool, develops vertical columns, whereas in the vertical walls it develops horizontal columns.

Most of the jointing of sediments is due to earth movement, and is often very regular in direction through great depths and over wide areas—though the closeness of spacing depends largely on the material: joints are sometimes only a fraction of an inch apart; at other times many feet. Cleopatra's Needle in London is one of the longest unjointed stones in the world. It consists of granite from Egypt. It is said that a slightly longer mass was measured in the Ross of Mull granite in connection with a proposed monolith to commemorate Queen Victoria's consort. The monolith was not extracted, but all the same the base of the Prince Consort monument at Kensington does consist of Ross of Mull granite.

It is thought by many that jointing has to a large extent been caused during the propagation of earthquake waves. The best argument in support of this view is that joints often traverse the boulders and pebbles of conglomerates, as was noticed very early in the history of Geology in regard to conglomerates at Oban. This certainly suggests that the joints in question have been formed by a sudden snap. If they had been produced slowly, in response to gradually accumulating stresses, one would expect them to bend round and avoid hard boulders, merely breaking the soft matrix.

A very puzzling superficial system of joints is sometimes developed, especially in granite, and is called sheet jointing. It is splendidly exhibited in Arran, where conspicuous joints roughly correspond in direction with the major, not minor, surface slopes of the granite mountains and glens of the north part of the island (Fig. 47). It has been suggested that these joints are produced by alternate heating and cooling of the surface controlled by diurnal, seasonal or climatic changes, or else by swelling of the surface due either to chemical decomposition or to relief from pressure as a result of erosion. All suggested explanations at first sight seem inadequate, but there is no doubt of the reality of sheet jointing, however it originates. It may be

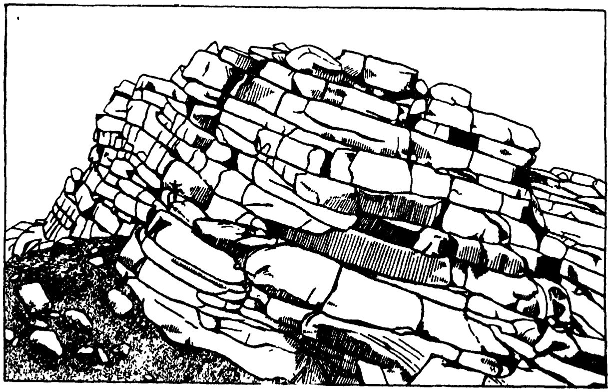

FIG. 47. Sheet jointing in granite, Arran. (Geol. Surv. photo.)

added that the extremely delicate instruments, with which records of distant earthquakes are taken, show that every day our valleys open a little, to close again at night. This is a result of superficial heating and cooling.

Joints, however produced, co-operate with bedding in guiding erosion. Most steep or vertical features in scenery are directed by joints. This applies in relation to long lines of cliff in the open, with all their detail of stack and pinnacle, and to the walls of gorges and caves. Here it is convenient to say a few words about the term escarpment. Escarpment, in common and military English, means a cliff or steep slope. In Geology it has the same meaning, but is especially applied to a cliff or steep slope that constitutes the edge of an outcropping bed or formation.

One of the most ordinary features produced during the erosion of sediments, lavas and sills is a combination known as escarpment and dip slope. Consider a resistant sandstone interstratified between unresistant shales. The shales above are soon stripped away to leave the top of the sandstone exposed, thus giving a slope corresponding with dip. The shales below, when once they are laid bare, are also cut away, and this leads to undermining of the sandstone. The latter breaks along joints and furnishes a cliff or escarpment.

Artificial excavation, like erosion, is much controlled by joints. For instance, before the introduction of steam shovels, it was sometimes easier to excavate granite, because it is jointed, than boulder clay, which is unjointed.

Jointed rocks are particularly readily worked up the slope of the most gently inclined set of joints, often that which follows the bedding. This puts at least one of the other two sets of joints into an overhanging position relative to the quarry, so that by blasting or wedging it is specially easy to dislodge a mass. The Ballachulish granite quarries were laid out on this plan. *Facilis descensus Averno* is an old saying. This method of quarrying has proved all too easy, it is actually dangerous ; and so nowadays it is illegal in Britain to work with an overhanging quarry face.

In the case of comparatively thin limestone outcrops on level ground, such as are common in Scotland, the quarryman may not be able to make the best use of the jointing, because he may have no other choice but to follow the rock down to the dip. In coal, however, which is so valuable that it is quarried far below the ground, the miner can advance with due regard to the direction of jointing, or cleat, as he calls it. His choice has an important bearing upon the ease of getting the coal, the size of coal produced, the control of roof strata, and the safety of the workmen. For instance, in a coal of a hard nature, the working face is usually kept parallel with the main cleat, which helps the coal to fall away when undermined. Whereas in soft coal such an arrangement, especially if the working is up the dip, may endanger the workmen and produce too much small coal. To meet this difficulty the working face is adjusted at some chosen angle, sometimes even at a right angle, to the main cleat.

CHAPTER XXI

NORMAL FAULTS

FAULTS are fractures in rock, along which there has been displacement of the material on the one side with respect to that on the other. The name is of old standing, and comes of the trouble which such fractures give to miners and quarrymen.

Faults are of three main kinds. In this chapter we shall only deal with the class known as normal faults, so called because they are the ordinary faults in rocks which have been but slightly folded.

A normal fault is inclined, and relative sliding movement has occurred down the slope of the fault.

The slope of any fault is called the hade. It has direction and amount, and the latter is measured in degrees from the vertical. Most normal faults are steep with a hade of about 15°.

A fault strikes at right angles to its hade.

The vertical component of a fault's displacement is called throw. Quite a number of Scottish normal faults have a throw much exceeding 1,000 feet. The Campsie and Ochil faults are two very large faults in the Midland Valley of Scotland.

The horizontal component of a fault's displacement, measured at right angles to strike, is called heave. With a hade of 15°, heave is quarter as big as throw. Thus a 1,000-foot fault is likely to have a 250-foot heave.

The heave of a normal fault increases the length of a country at right angles to the strike of the fault. Normal faults are therefore a result of actual or relative tension.

When faults are moving they lift, or lower, the landscape. Immediately afterwards, erosion sets to work to level down the unevenness produced. In our own country erosion has overtaken earth movement, to such an extent that probably no cliff or steep slope exists in Britain, which is the direct result of earth movement. Faults, however, often influence the scenery of our country, since they may bring together outcrops of hard and soft material, and erosion tends always to leave the hard standing up a bit above the soft. It is good practice to draw a section showing a hard formation interstratified between two soft formations, the whole inclined and faulted, and to insert erosion surfaces at successively lower levels.

In ancient faults there is generally nothing to tell us whether the one side has gone up or the other down ; but the side which relatively has moved up is called the upthrow side, and the side which relatively has moved down is called the downthrow side. On geological maps a fault is shown by a line, generally with a special colour or ornament, and the downthrow side is indicated by a tick.

We may now re-define a normal fault as one that hades in the direction of downthrow.

The hade of an exposed fault can be measured in the field with the same instrument, clinometer, as is used in measuring dips.

On a map faults generally cross valleys without appreciable V-ing, because they are so steep (Fig. 48). If the V can be recognised it points in the direction of hade.

In the simple maps that students handle during a first-year course, it is well to assume that all faults are normal, and to draw them in section hading towards the downthrow.

Now let us consider how faults are discovered.

A fault is sometimes exposed, in which case its position is marked by a belt of broken rock, accompanied by scratches called slickensides, and by polishing. If the fault is considerable the rocks on either side are often of different character and attitude, as shown by bedding.

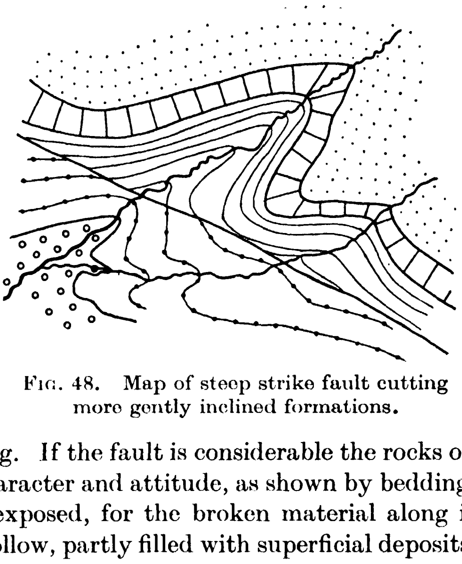

FIG. 48. Map of steep strike fault cutting more gently inclined formations.

Often a fault is not actually exposed, for the broken material along it tends to be worn away leaving a hollow, partly filled with superficial deposits. The existence of such a hollow, running across country in a straight line, immediately suggests the presence of a fault. One of the biggest faults in the world is the Great Glen Fault of Scotland. Its course is marked from Fort William to Inverness by an erosion hollow followed by lochs, rivers, roads and the Caledonian Canal. The crushing of the rocks exposed along the seashore near Fort William is amazing. Of course as a rule the hollows along fault outcrops are on a relatively minute scale.

•Often, even when a fault is not marked by any special feature in the landscape, its presence is self-evident, for different formations may be seen aiming at one another across its position. Thus if the eastern part of a hill slope is made of flat sandstone, and the western part of flat limestone, one is pretty safe in concluding that the two formations are separated by a steep fault. Sometimes in ill-exposed country the evidence may well escape the attention of a beginner, and yet be quite obvious to a trained worker. A sudden change of dip is one of the phenomena that makes a geologist look about him and take notice. Dips change with folding, but as a rule not very abruptly ; whereas they do very often indeed alter quite abruptly at a fault.

A geologist in the field always records his observations of outcrop, dip, etc. on a map. Faults may often become much more apparent when the evidence has been assembled for a considerable area. Again and again one realises on looking at a map that formations are aiming at one another across some particular line that must be marked as a fault.

The more the strike of a fault diverges from the strike of the bedding, the more obvious is the fault upon a map. In the extreme case a fault may strike in the direction of the dip of the bedding. Such faults are called dip faults.

Let us consider for a moment the effect that a dip fault has on outcrops. At the time of its formation such a fault does little else than raise part of the outcrop to a higher level. The resultant displacement, though very obvious in the field, does not show on a map, except on the actual fault face, which is exceedingly narrow. Erosion, however, tends to cut down the upthrow side to the same height as the downthrow side. If you draw a section you will see at once that this carries the outcrop on the upthrow side back in the direction of dip. In this sense dip faults are said to displace outcrops horizontally. The effect is so noticeable that it is not likely to escape detection either in the field or on a map upon which observational data have been recorded.

The other extreme is the strike fault, which follows the strike of the formations. It may be much more difficult to detect, if not actually exposed. Criteria which sometimes help are as follows (in every case it is assumed that the formations mentioned are conformable) :

(1) Two adjacent formations dipping towards or away from one another (Fig. 49).

(2) A sudden change of dip.

(3) A younger formation dipping towards an older (for instance, where downthrow opposes dip).

(4) Omission of outcrops in a known sequence (for instance, where downthrow helps dip).

(5) A straight, and therefore steep, boundary between two formations running across a valley, in contrast with neighbouring V-ing outcrops that indicate gentle dips (Fig. 48).

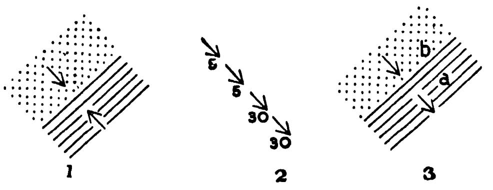

FIG. 49. Indications of strike faulting.

1. Two formations dipping towards one another.
2. A sudden change of dip.
3. A younger formation, b, dipping towards an older formation, *a*.

The direction of downthrow of a fault is determined in one of two ways :

(1) Direction of hade.—Hade can be seen in any natural section of a fault, and also in artificial sections such as coal mines. Normal faults are so characteristic of gently folded country that one is seldom wrong, in such a country, in assuming that the downthrow is in the direction of hade. It may be added that plans of underground workings in coal seams show the hade of a fault very clearly if more than one coal seam has been worked up to the fault. The trace of a fault that hades west occurs successively farther west in each lower seam.

(2) Younger formation against older.—If two formations that can be dated are brought together by a fault, then obviously the younger formation must mark the downthrow side, because previous to faulting it was at a higher level than its neighbour (if we leave out of account complications that may be introduced by a dip greater than the inclination of the fault itself). This principle applies equally in the field or in map reading. Here is a method that is often of use in actual practice in map reading. If a fault cuts across outcrops and produces a displacement, place a finger of each hand on the outcrop of one and the same formation on the two sides of the fault, each finger pointing in the direction of dip. Then the lower finger is on the downthrow side.

To determine the amount of downthrow, draw a section to scale across the fault, taking care that the section is drawn at right angles to the fault and that the resolved dip of the formation and the hade of the fault are properly shown ; then the vertical component of displacement is the throw. The amount in feet may be written along the mapped course of the fault, on the downthrown side.

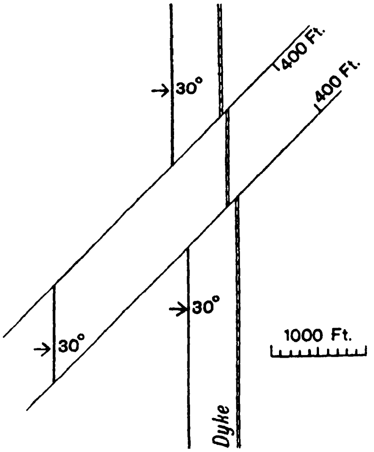

Fig. 50. Map showing the effects of downthrow and heave upon dipping and vertical outcrops, subsequently eroded to a plain.

Although First Year Students need not trouble about such details, it is interesting to realise that the outcrop-displacement produced by a normal fault is partly due to heave. At first sight it might be thought that a dipping outcrop, after crossing two equal and opposite faults, would carry on along the continuation of its old course, undeflected. This is not the case, unless the outcrop crosses the faults at right angles. The two faults, it must be remembered, have broadened the country by the amount of their combined heaves, and therefore produce a corresponding displacement in any outcrop which they cut (Fig. 50). In the case of vertical beds or dykes, the heave-displacement at each and every fault is the only mappable feature, for downthrow-displacement vanishes. This heave-displacement gives no indication of the direction of downthrow (Fig. 50).

There is another aspect of heave which is of very great importance to mining geologists. If you draw a section you will readily understand that a vertical bore hole, which passes through a normal fault, always misses part of the section. Thus it is well, when boring for coal, to choose a site that is not on the downthrown side of a neighbouring fault. Faults are so common in Scotland and some parts of England that it may be impossible to avoid them in boring. The presence of a fault in the cores brought up from bores may be marked by broken slickensided rock. Sometimes, however, it escapes direct detection, because broken rock may come up in an indecipherable slush. In such cases faults are recognised, and allowed for, by comparing the journals of neighbouring bores.

Faults have an engineering importance as broken belts of rock that :

(1) in wet rocks, serve as a source of water, desirable or undesirable ;
(2) in dry rocks, allow of leakage of water from reservoirs ;
(3) in any rocks, furnish weak foundations ;
(4) in regions of modern movement, such as California or Japan, are liable to displacement with disastrous results.

Faults in combination determine certain structures that have been given special names :

A graben (German for trench, cognate with our grave) is a subsidence bounded on two sides by parallel faults throwing down towards the interior. Another name is fault trough (Fig. 50).

A horst is an elevation bounded by faults throwing down towards the exterior.

Step faults are two or more parallel faults throwing successively in the same direction.

All these fault structures at the time of their development make corresponding geographical features, but these are liable to be obliterated by erosion and deposit. The Jordan Valley in the Holy Land, and the Great Rift Valley in East Africa, are modern grabens that still retain much of the form given by earth movement. Professor Gregory, before he came to Glasgow, took a very prominent share in the investigation of the Great Rift Valley. He went out as a younger member of a British Museum expedition, and, when the seniors fell ill, carried on with his native party alone in a semi-hostile country.

CHAPTER XXII

CONCRETIONS AND VEINSTONES

CONCRETIONS

CONCRETIONS are natural growths of mineral matter, which form about a centre or core.

The growth may take place in superficial water, or, more commonly, underground. Concretions serve therefore as a link between the chemical precipitates among sediments and the underground chemical precipitates known as veinstones. Concretions give us many examples of the approximate balance of solution and deposition, already noted in connection with stalactites. Material dissolved at one point may be reprecipitated close at hand. Often one can see a cause for such reprecipitation, since many concretions, but by no means all, have grown about a decaying organism. Any concretion that can be described as a lump may be called a nodule.

The commonest minerals to give concretions are : calcite, forming limestone nodules ; siderite, forming ironstone nodules ; flint and chert. The texture is generally very fine, but sometimes coarse. Thus, in exceptional districts (Fontainebleau and the Bad Lands of South Dakota), one finds large well-formed crystals of calcite full of sand grains. Other somewhat mysterious examples of the concretionary growth of large crystals are furnished by the post-Glacial muds of the Firth of Clyde and certain other estuaries.

Concretions are usually either irregular or spheroidal in form. If spheroidal they lie flattened along the bedding.

The flints of the Chalk formation, called chalk flints for short, occur as irregular nodules or bands roughly following the bedding, but also to some extent distributed along transverse joints. They have derived their material from siliceous sponges disseminated through the chalk. Not infrequently they have grown about some fossil such as a sea urchin. The solutions that brought the flint carried away an equal volume of chalk, so that the nodule replaces country rock. In some cases, however, concretions displace country rock in the same way as growing ice crystals may lift gravel.

There is a particular type of limestone nodule, called kankar, extensively worked for lime in tropical parts of India and East Africa. The nodules are dependent for their formation on an alternation of wet and dry seasons. They are irregular in form, though with a distinct vertical tendency, and are of very fine-grained smooth texture. The top division of the Upper Old Red Sandstone, and also of the New Red Sandstone, in Scotland carries limestone nodules, called cornstones, which in form, attitude and character precisely resemble the kankar nodules of to-day. They furnish evidence that at the time of their formation Scotland was dry land with a tropical climate of alternating wet and dry seasons.

The vertical tendency of cornstones, though generally ill expressed, is sometimes spectacular. There are rows of cornstone nodules in the Upper Old Red Sandstone of Arran that look like a group of organ pipes.

VEINSTONES

Veinstones are underground chemical deposits or replacements, formed along joints or faults. They have very often been supplied by igneous emanations.

Veinstones may be divided on a commercial basis into gangue, which is the comparatively worthless portion, and ore, which is the comparatively valuable portion. Often, as new uses are found for uncommon metals, part of the gangue of one generation of miners becomes ore to the next ; and spoil heaps are worked over to extract material previously treated as waste.

Minerals that are frequently grouped as gangue include :

Quartz (hexagonal)	SiO_2
Calcite (hexagonal)	$CaCO_3$
Fluorspar (cubic)	CaF_2
Barytes (orthorhombic)	$BaSO_4$
Tourmaline (hexagonal)	Borosilicate of Al and Fe

The first three have been mentioned in previous chapters.

Barytes is white when pure, has a good cleavage and the hardness of calcite (H3, *see* scale of hardness, p. 67), but does not fizz with acid, and is very heavy for its size. In fact its high specific gravity is distinctive. Barytes is often called heavy spar, while the name barytes itself comes from the Greek for heavy.

Tourmaline occurs in long three-sided or six-sided lustrous prisms, easily distinguished from hornblende by optical tests.

Among the ore minerals may be mentioned :

Gold (cubic)	Au
Pyrites (cubic)	FeS_2
Haematite (hexagonal)	Fe_2O_3
Siderite (hexagonal)	$FeCO_3$
Silver (cubic)	Ag
Argentite (cubic)	Ag_2S
Galena (cubic)	PbS

Zinc Blende (cubic) - - - -	ZnS
Copper Pyrites (tetragonal) - - -	$CuFeS_2$
Malachite (monoclinic) - - -	$CuCO_3 . Cu(OH)_2$
Cassiterite or Tinstone (tetragonal) -	SnO_2
Stibnite (orthorhombic) - - -	Sb_2S_3
Cinnabar (hexagonal) - - - -	HgS

It will be noticed that these veinstone minerals, except tourmaline, have simple compositions. In this they differ from the complex silicates that make up the bulk of igneous rocks. In correlation with their simple chemistry they crystallise for the most part in the two systems that have the highest symmetry, a matter that we yet have to consider. These two systems are the cubic, with three equal axes at right angles, and the hexagonal, with three equispaced equal axes in one plane and a fourth unequal axis at right angles to this. Copper pyrites, malachite, cassiterite and stibnite are exceptions. The long form and corresponding cleavage of stibnite are very distinctive, taken in conjunction with its metallic grey lustre.

All the ore minerals listed have metallic lustre, except siderite, zinc blende, malachite, cassiterite and cinnabar. We have already dealt with siderite, which can easily be recognised as a carbonate by treatment with warm acid. Zinc blende and cassiterite both have adamantine lustre and tend to be slightly transparent. Malachite is green, and cinnabar is red. Fortunately the latter is softer (H 2) than haematite (H 6), and of higher specific gravity.

All coloured minerals with metallic lustre give a black or coloured streak, which further separates them from the silicates. The colour of the streak, as already pointed out, is not necessarily the same as that of the lustre, for pyrites has a black streak. Of the ores without metallic lustre, the highly coloured malachite and cinnabar give green and red streaks respectively, and zinc blende and cassiterite give rather indefinite pale brownish streaks. The best rough test with which to distinguish zinc blende from cassiterite (in absence of a microscope) is hardness. Zinc blende (H 4) is scratched with a knife, and cassiterite (H 7) is not. Hardness is also very useful in distinguishing copper pyrites (H 4), which is scratched with a knife, from iron pyrites (H 6·5) which is not.

As in the case of the minerals of igneous and sedimentary rocks, a first year student is expected to get to know a good deal more than is here set down. He should examine the minerals themselves with the help of a book of reference, such as Rutley's *Elements of Mineralogy*.

The simple chemical composition of the gangue and ore minerals is responsible, not only for the high symmetry of their crystallization, but also for their habit of occurring in veins. These simple compounds tend to separate along with water vapour from the crystallizing silicates.

Tourmaline accompanies the veinstone minerals because of the volatility of boron compounds.

In several cases it is found that there is a distinct zonal arrangement in the deposit of ores in Nature, just as there is a zonal arrangement in the deposit of volatile substances in the chimneys of smelting furnaces. Cornwall gives a good example. For the present purpose it is sufficient to mention merely the metal, without particularising the ore. The following is the order, starting from the hottest region at the time of deposition, that is from within, or just outside, the Cornish granites: tin, copper, zinc, lead, lead with silver, iron.

Thus a mine, which started on the outcrop of a copper vein, may find itself in depth a tin producer.

Similar zoning is met in other fields. Butte, of Montana, the greatest copper camp in the world, shows very clearly an exterior upper zone of zinc and an interior lower zone of copper.

The mobility of the ore solutions makes it easy for chemical reactions to occur with resultant replacements. In fact replacement is a much more important phenomenon in ore geology than in igneous geology. The products depend, partly upon the nature of the ore solutions, and partly upon the nature of the country rock. In Cornwall, where the granitic emanations were rich in boron, and the country rock was slate, tourmaline has been produced on a considerable scale. Limestone is a rock that is very susceptible to chemical alteration, and in many parts of the world rich ore-replacements are worked in limestone as country rock.

Very important changes affect ores as a result of long-subsequent weathering. There is a tendency to oxidize the metallic sulphides near the present level of the ground, and to remove the resultant sulphates in solution. Thus an impoverished or leached zone is produced, which may mask riches still left underground. Where, for instance, the copper veins of Butte reach the surface they carry no copper at all. They were worked for their small content of silver, and this led miners down to the unoxidized depths where copper is abundant.

Very often the leached zone is counterbalanced by a zone of secondary enrichment farther down. Descending solutions may undergo complex reactions leading to precipitation of insoluble compounds. The material of these concentrations may have come in part from portions of the leached zone now actually eroded away. In many fields the zone of secondary enrichment is all that is worth working.

Sedimentary sorting may produce rich accumulations at the surface. Alluvial gold and stream tin are cases in point. The heavy valuable material is concentrated by natural currents, just as it is in the artificial currents produced by panning. Another name for alluvial gold is placer gold.

CHAPTER XXIII

TECTONICS

WE shall now consider structural map-reading on a more quantitative basis than before, and then pass on to certain additional aspects of folding and faulting. Some familiarity with tectonics is an essential preliminary to the understanding of the Metamorphic Rocks which are to follow in Chapter XXIV. The present chapter is to be regarded as a sequel to Chapters IV, X and XXI.

DIP AND VALLEY-SLOPE.—The following four propositions may be regarded as self-evident, but nevertheless are useful.

(1) If an inclined bed is cut through by a valley, and if the outcrop of the bed does not reach the valley floor either upstream or downstream, then the component of the dip parallel to the valley must equal the bottom-slope of the valley.

(2) If a bed crosses a valley undeflected, it must be vertical.

(3) If a bed V's downstream the downstream component of its dip must be steeper than the bottom slope of the valley.

(4) If a bed V's upstream, its dip may be at any angle not included in (1), (2) and (3).

STATEMENT OF DIP.—Dip can be expressed either in degrees, or in the form 1 in so many. Approximately :

$$1^\circ = 1 \text{ in } 60$$

and, up to 30°,

$$n^\circ = n \text{ in } 60 = 1 \text{ in } 60/n$$

This rule, $1^\circ = 1$ in 60, is very easy to remember because it is connected with the ancient habit of dividing units into 60 parts, since 60 has many factors. Thus we have in time :

60 seconds = 1 minute
60 minutes = 1 hour

and in angles :

60 seconds = 1 minute
60 minutes = 1 degree
60 degrees = 1 angle of an equilateral triangle

Very roughly, the angle of an equilateral triangle = 1 in 1, which helps us to remember that much more closely $1^\circ = 1$ in 60.

DIPS AND CONTOURS.—The 1-in-so-many method of expressing dips is useful in the graphical solution of problems. Suppose we are working on a large-scale contoured map, and that an outcrop in crossing a valley cuts the 400-foot and 300-foot contours on the two sides of the valley. Obviously the line of strike is obtained by drawing a line through the two points at which the outcrop cuts the 400-foot contour. Also a parallel line should be obtained by drawing a line through the two points at which the outcrop cuts the 300-foot contour. Suppose these two lines are x feet apart on the map. Then the dip is 100 feet in x feet, or 1 in $\frac{x}{100}$.

DIP IN BORES AND QUARRIES.—A related problem is to determine dip from records of bores. Suppose a coal has been met in three bores, at sites which we may call A, B and C. If we know the relative heights of these sites, and the depth at which the coal was met at each of them, it is easy to calculate the component, or apparent, dip from A to B and from A to C. Let us suppose that we find a component dip from A to B of 1 in 12, and from A to C of 1 in 5. Then in the line AB mark B', where $AB' = 12$ inches (or any other unit such as centimetres); and in the line AC mark C', where $AC' = 5$ inches. Obviously $B'C'$ is a line of strike, along which our coal is the map-equivalent of 1 inch lower than at A. From A drop AD, a perpendicular, on to $B'C'$. Then AD is the line of dip. Also if $AD = x$ inches, then 1 in x = amount of dip.

An exactly similar construction allows us to calculate the true dip from two observations of component dips taken along the walls of a quarry.

THICKNESS.—The thickness of a formation is measured at right angles to the bedding. It can often be measured directly in an exposure, especially if the exposure consists of a cliff or series of cliffs, standing at right angles to the bedding. In such a case a succession of partial measurements is made with a foot rule. It is not necessary that these partial measurements should follow one another in a straight line, so long as immediately successive measurements stop and start at one and the same bedding plane.

A problem which often presents itself is to calculate the thickness of a formation from the breadth of its outcrop and the amount of its dip. This is done very conveniently by drawing a large section to true scale, using the observed dip and reading off the thickness at right angles to the bedding.

DEPTH.—Another closely allied problem is to determine the depth of a stratum such as a coal seam at some particular point. A section is drawn through the point to the outcrop of the stratum, and the depth is read vertically.

Geological surveyors generally carry about short mathematical tables in their pockets, which give answers in regard to thickness and depth without the trouble of drawing sections. The tables need only be very short indeed.

OVERFOLDING

We have several times had occasion to speak of strata turned vertical or even upside down. In the latter position they are said to be inverted or reversed, whereas strata, which have not been inverted, are called normal, because this is the usual attitude.

The definitions of anticline and syncline, which have so far been given (Chapter IV), describe folds in which both limbs are normal. Here is a general definition of an anticline, which holds even where one limb is inverted :

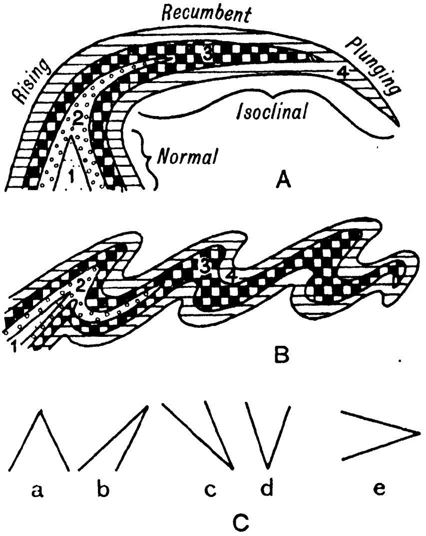

Fig. 51. A and B are anticlines, which deserve to be called recumbent because each has a large horizontal component in its cross-strike extension. The stratigraphical succession is from 1, oldest, to 4, youngest. In C, a and b represent antiforms, closing upwards ; c and d, synforms, closing downwards ; e is a neutral recumbent fold said to close towards a particular point of the compass.

An anticline is a fold with a core of originally underlying rocks (Fig. 51A, B).

The converse holds for syncline.

The following definitions are very easy to remember :

A normal fold has both limbs normal.

A normal fold is symmetrical if its two limbs are equally inclined in opposite directions.

An overfold or overturned fold has one inverted limb.

An overfold is isoclinal if the normal and inverted limbs are roughly parallel.

An overfold is recumbent if the two limbs are roughly flat.

The axial plane of a fold as nearly as possible divides the fold into two equal parts parallel with strike.

The axial plane is vertical in a normal symmetrical fold, but becomes inclined in a normal asymmetrical fold, and continues so in an overfold, until it reaches the horizontal in a recumbent fold.

An axis of a fold is the line in which any bed intersects the axial plane.

Pitch is the inclination of a fold axis.

Pitch may be difficult to read accurately on a map, but the following rule gives very useful results.

The pitch of a fold outcropping on level ground roughly corresponds with the dip of the beds in the central part of the fold, where the dip is at right angles to that of the limbs.

This rule does not hold for recumbent folds.

The pitch of an overfold, if observable, allows us to decide whether the overfold is an anticline, or a syncline (supposing it is not recumbent). This is of very great importance, because in an isoclinal overfold, the dips of the limbs do not give us the requisite information. The rule is quite easy to understand; it is as follows: if you look at a map along the direction of pitch, the anticlines and synclines will have the same general appearance as if seen in section. For example, if you examine the map of Fig. 52, first along the pitch, that is with the north-east corner directed away from you, and then in the opposite direction, you will see that, with the former orientation, all the anticlines look like anticlines, whether they are normal or isoclinal. It is comforting to realise that inversion of pitch is a very rare phenomenon in comparison with inversion of dip.

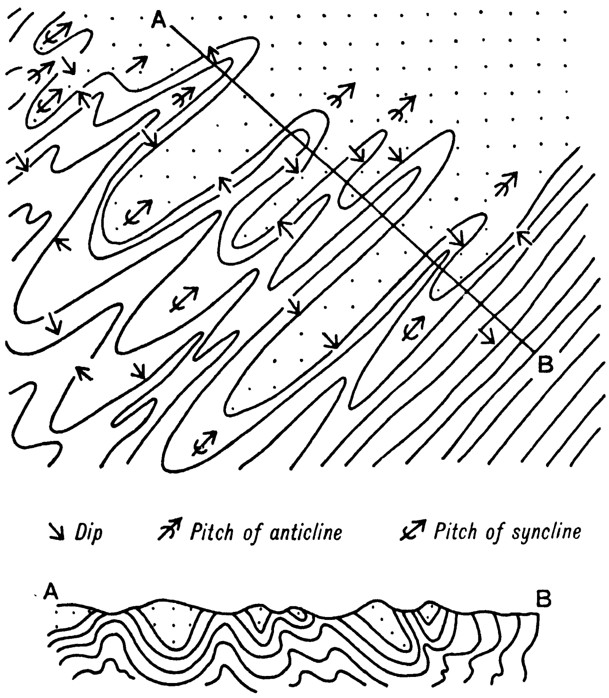

FIG. 52. Map and section of a pitching series of folds, some normal, others isoclinal.

To distinguish an anticline from a syncline in regions of great tectonic complexity (*cf.* Fig. 51A and B), we need to know, not only the geometry of the formations in the exposure which is being studied, but also something of the history of the fold. For a variety of reasons, it is sometimes convenient to be able to give observed folds names which have an entirely geometrical significance (Fig. 51c) as follows :

Antiform means a fold that closes upwards.

Synform means a fold that closes downwards.

TEAR FAULTS

A tear fault has a horizontal displacement parallel to its strike. In a pure tear fault there is no downthrow. The hade of a tear fault is generally steep.

Tear faults are very hard to distinguish from normal faults, unless they cross the axes of normal folds, or cross vertical beds or intrusions striking at right angles to themselves. If a tear fault crosses an anticline it will move the whole anticline in one direction ; whereas a normal fault, coupled with erosion, displaces the two limbs in opposite directions. Kennedy has recently claimed that the Great Glen Fault of Scotland is a tear fault, and that the Strontian and Foyers granites, which it truncates, are really the two halves of a single intrusion separated by 65 miles of horizontal movement.

Horizontal slickensides are also clear evidence of tear faulting. One must, however, be careful not to assume that because a fault has functioned as a tear fault at one stage of its career that its most important movements have been of this character.

REVERSED FAULTS OR THRUSTS

A reversed fault, or thrust, hades away from the downthrow (this is an introductory definition to be modified in the following section on *Slides*).

The hade is generally low, so that the heave, or horizontal displacement at right angles to the strike of the fault, is often great compared with the throw. There are many reversed faults, or thrusts as they are commonly called, with a heave of more than ten miles in extent. The Moine Thrust of the North-West Highlands is one of the best known in the world (Figs. 290, 291). Its outcrop is visited every year by British and foreign geologists, merely for the thrill of seeing it. There is an excellent model of it in several museums, prepared by Peach and Horne, who mapped it for the Geological Survey. Students are lucky if they can study this model. At any rate they can buy the penny illustrated guide published by the Geological Survey.

The heave of a reversed fault shortens a country. Reversed faults are therefore compressional phenomena, and that is why they are called thrusts (*cf.* Fig. 54).

The direction of relative overthrust is called for short the direction of movement. This is a matter of definition rather than of abstract physics.

Crushing phenomena are generally more pronounced along thrusts than along normal faults. A consolidated drawn-out rock-powder, produced by faulting, is called mylonite, meaning milled rock. Mylonite is commonly found along important thrusts, such as the Moine Thrust.

Here are a few more definitions :

A thrust-mass or, to use a French word, nappe, is the sheet of rock that has moved forward on top of a thrust. We are familiar with the word nappe in its diminutive napkin.

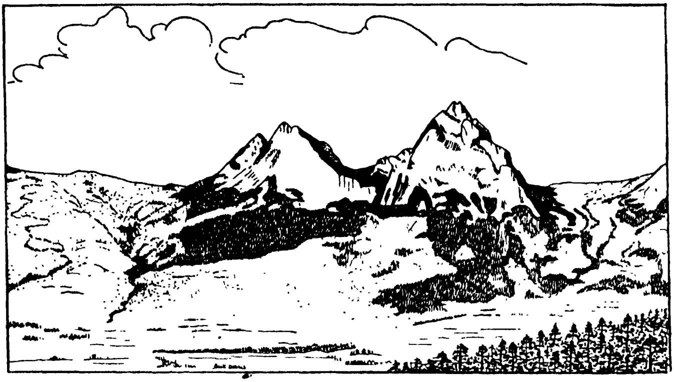

FIG. 53. The Mythen klippe, near Lake Lucerne.
(Wehrli-Verlag photo.)

The rocky peaks are far-travelled Mesozoic. The foundation, on which they lie, is Tertiary concealed under grass and forest. In the right foreground is a forested dip slope of Cretaceous emerging from beneath the Tertiary.

A klippe is a portion of a nappe isolated by erosion (Figs. 53, 291). The word is German and means cliff. Some of the conspicuous klippes of the Carpathians and Alps are bounded by cliffs, but this is not a necessary condition. For a time the Alpine klippes were mistaken for cliff-bounded islands, with later formations banked up around them.

A window is an eroded gap in a thrust, through which one can look down upon the rocks below the thrust.

TECTONIC CONTRASTS

The earth's surface can be divided into :

(1) PERSISTENT PLATFORMS.—These through long ages have moved up or down with scarce appreciable tilt. Such platforms have persisted for very different periods of time. Among the most persistent are parts of Russia in Europe and the Great Plains and the Canadian Shield in North America.

These two immense platforms have refused to bend since before Cambrian times to the present day.

(2) FOLDED MOUNTAINS.—These have been subjected to an intense folding with the production of overfolds, thrusts and slaty cleavage. Folded mountains are of various dates. Most of Britain lies within the Caledonian range, which is largely of post-Silurian pre-Devonian date with its north-western front at the Moine Thrust (Fig. 278). Southern Britain and most of France and Germany lie within the Hercynian range, of post-Carboniferous pre-Permian date (Fig. 308). Switzerland, Italy and the Pyrenees belong to the Alpine range of Tertiary date, which extends eastwards through the Himalayas.

The Caledonian and Hercynian chains are very old, while the Alps are relatively young. The ancient ranges belong to Geology rather than Geography. We all agree that the Alps in Switzerland are mountains, because, being young, they stand high. Given time they will lose their height through erosion. They will then cease to be mountains geographically; but their roots will retain mountain structures, such as folds and thrusts. Geologically speaking we claim that folded mountain chains are indestructible. It is geographical nonsense to speak of the Caledonian chain running across the North Sea from Scotland to Norway; but it is true all the same, if we are thinking in terms of Geology.

The date of a mountain chain is deduced as follows:

A chain is of later date than the latest strongly folded formation that occurs within it. It is of earlier date than the earliest unconformable formation of its district which has escaped strong folding.

Mountains are not made in a day, so that when we come to detail we can often divide the period of active folding into stages marked by a succession of angular unconformities.

Most of Britain has approached, though very imperfectly, the condition of a persistent platform since the folding of the Caledonian chain at the close of Silurian times. The Old Red Sandstone, which represents the Devonian, lies at the base of a comparatively unfolded assemblage of formations. This condition does not hold true in the south of Ireland, England and Wales, where Hercynian folding came much later, and where the flat formations start with the Permian instead of with the Devonian.

The origin of folded mountains is uncertain. They have clearly resulted from compression; but the displacements involved are immense, and it is difficult to know whence comes the motive force.

It used to be thought that the interior of the earth must be cooling, because heat is escaping. If it is cooling it must be shrinking, and this would leave the already cooled crust too big for the interior. It has been suggested that the folded mountains may be compared with the wrinkles that develop on the skin of a shrinking apple.

This explanation has been disputed, especially since the discovery of radium. It is certain that if radium were as abundant throughout the earth as it is at the surface—and even there it is very scarce—it would supply more heat than is at present escaping from the surface. If so the earth is heating, not cooling. Probably in some way an approximate balance has been struck. The problem is far too complex to discuss here. All one can say is that at present there is no evidence that folded mountains are the product of a cooling earth.

The folded mountains with their immense thrusts are clear evidence that different portions of the earth's crust sometimes move towards one another for considerable distances. Reference has already been made to the hypothesis of drifting continents. It is thought by many that folded mountain chains are a symptom of this drift; that the Alps, for instance, were raised during a collision of the European and African blocks.

Those who adopt the drifting of continents as an explanation of folded mountains have still to find a satisfactory motive force. Convection currents in the layer below the continents have been postulated; but the subject is too deep for ordinary geologists.

Perhaps it is well to point out that though the drifting of continents is a very hypothetical idea, the floating of continents seems to be established. It is pretty clear that the several continents are made of relatively light material which does not extend in bulk far under the intervening oceans. As for the interior of the earth, it is certainly denser than the common rocks of the continents. One pictures the continents floating something like icebergs with much of their light material submerged. The idea is summed up in the word isostasy, which claims that the major features of geographical relief are in equilibrium with the underground distribution of density. Gravity determinations seem to demonstrate that the Himalayas, for instance, are buoyed up by a great downward bulge of light continental material, projecting into a heavy substratum.

SLIDES: THRUSTS AND LAGS

The definition of thrust, which has been given above, is useful for introductory purposes, where it is convenient to contrast thrusts with normal faults. In actual practice, the need soon arises for a more general definition, one that can be widely applied without self-contradiction. For instance, one and the same fault may be disposed in antiforms and synforms, which would (according to literal interpretation of our previous definitions) lead us to call it in some places a thrust and in others a normal fault. Let us begin our process of generalization by defining a term that is more inclusive than thrust, namely slide.

A slide is a fold-fault, or, in other words, a fault which has arisen in connection with strong folding.

We can then proceed as follows :

A thrust is a slide which more or less completely replaces the reversed limb (real or imaginary) of an overturned anticline.

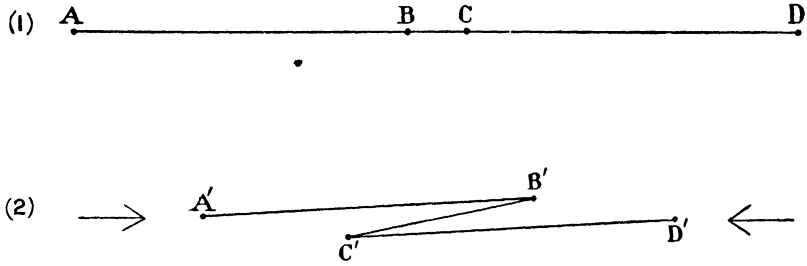

FIG. 54. Thrust tectonics with overlapping approach of AB and CD, both maintaining their original lengths. BC is rotated and thinned by elongation.

Let us consider the diagram (Fig. 54). If the elongation of *BC* into *B′C′* be due to faulting then a thrust lies along *B′C′* and partly replaces a real reversed limb. If again the original interval between *B* and *C* had been zero, then *B′C′* would represent a thrust replacing an imaginary reversed limb.

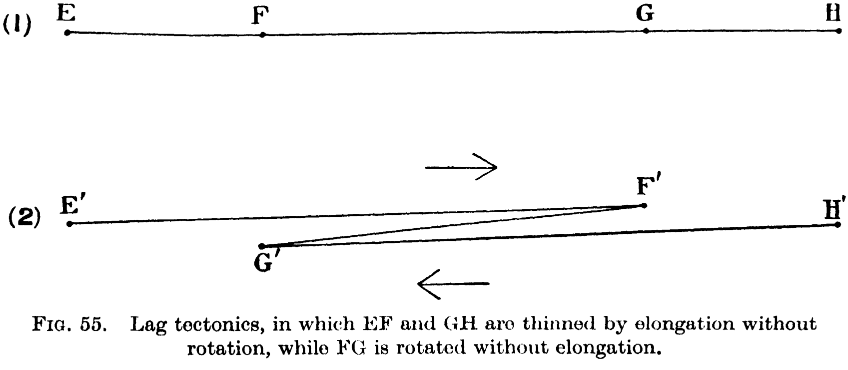

FIG. 55. Lag tectonics, in which EF and GH are thinned by elongation without rotation, while FG is rotated without elongation.

Our next definition is :

A lag is a slide which more or less completely replaces the unreversed limb of an overturned anticline (real or imaginary).

For introductory purposes Figs. 54, 55 suffice to convey the contrast between thrust and lag tectonics. In the former, rotation is subordinate as is indicated by the elongation (with thinning) of the rotated limb *B′C′*. In the latter, rotation is predominant, as is indicated by the elongation (with thinning) of the unrotated limbs *E′F′* and *G′H′*.

It is unnecessary to pursue the subject of lag tectonics farther, for it has comparatively few applications in Geology. It may, however, be pointed out that movements with a predominant rotation factor are conveniently called eddies. Lags are developed in connection with eddies, and are a feature of particularly deep-seated mountain-making movements (Fig. 289).

CHAPTER XXIV

METAMORPHISM

METAMORPHISM is a mechanical, or chemical, rearrangement of constituent material, generally with a development of new minerals. Processes of ordinary weathering, consolidation and cementation are excepted.

There are two great categories, contact and regional.

CONTACT METAMORPHISM is limited to the neighbourhood of intrusions, to which it is due. The belt of contact-altered rock adjacent to an intrusion is called an aureole.

Contact alteration may result from simple baking, in which case no new substances are introduced, while volatiles, such as H_2O and CO_2, tend to be expelled. Thus the hydrated silicates of aluminium, common in clay-rocks, are often converted by baking into andalusite, which is an anhydrous silicate of aluminium, Al_2SiO_5. Similarly, if an impure limestone is heated, the calcium tends to form silicates known as calc-silicates, which entails loss of CO_2.

Pure limestone, however, recrystallizes to marble, and does not decompose to lime, as it does when heated in an open kiln at atmospheric pressure. (Some of the marbles of commerce are merely unmetamorphosed limestones that are capable of taking a good polish.)

Rocks, other than marble, which have recrystallized under the influence of heat, are often called hornfels, if the new minerals have not developed with a parallel structure. Andalusite-hornfels and calc-silicate-hornfels are commonly found near granites in Scotland and elsewhere.

It is probable that the volatiles, expelled from neighbouring country rock during baking, may be in large measure dissolved, under pressure, by the magma, and allowed to escape at volcanoes.

In addition to mere baking, contact alteration often includes changes due to introduction at high temperature of such volatiles as H_2O and compounds of fluorine, F, and boron, B. When a magma consolidates to rock it has to get rid of most of its dissolved volatiles, whether original or picked up from country rock. Tourmaline and muscovite are characteristic products of this gaseous type of contact alteration, known as pneumatolysis (where *pneuma* means gas as in pneumatic tyre). Pneumatolysis is a phase of igneous activity that has given rise to many mineral veins.

REGIONAL METAMORPHISM is widespread, and not limited to the vicinity of intrusions. It almost always has two aspects, dynamic and thermal.

Dynamic metamorphism depends on the application of force or stress. The production of mylonite along a thrust is a restricted example.

Of much wider scope is the production of slate, with its new splitting structure called slaty cleavage. Slaty cleavage is a structure developed by deformation, which allows a rock to split along close-set parallel planes. It depends upon the shape and arrangement of particles, not of atoms as in crystal cleavage. Its metamorphic character is often shown by its development across bedding.

FIG. 56. Slaty cleavage crossing folded bedding. (Leith, 1914.)

The connection between cleavage and deformation is occasionally quite obvious to the naked eye. While most slates are altered muds, the beautiful green slates of Cumberland are altered volcanic ashes. The distortion and flattening of the fragments, making these ashes, are exceedingly clear. Even in ordinary slates the distortion of fossils may tell the same tale. So also the crumpling of bedding speaks of compression. Rocks exhibiting slaty cleavage are generally strongly folded, and the cleavage runs parallel with the axial planes of the folds (Fig. 56).

Two contributing causes to the development of slaty cleavage are the reorientation of flaky minerals already present and the orientated growth of new flaky minerals. If beeswax full of haematite flakes is deformed by pressure, the flakes set themselves at right angles to the pressure and give the mixture an artificial slaty cleavage.

Thermal metamorphism, combined with mechanical metamorphism, greatly aids the development of new minerals, and thus increases the grade of the regional metamorphism.

An argillaceous slate with increasing metamorphism passes through the conditions of phyllite, mica-schist and paragneiss, terms that we shall presently define. First of all we must explain a rather difficult word, foliation.

Foliation is a parallel arrangement of new minerals, either along planes or along lines. Often the new minerals are arranged in alternating leaves or plates (folia), which may, or may not, make an angle with the bedding (*folium* in Latin means leaf; some leaves, of course, such as those of pine trees, are linear).

The origin of such folia is not always understood.

Slates often are sufficiently recrystallized to be classed as foliated, in which case foliation and slaty cleavage coincide. More metamorphosed rocks such as phyllite are always foliated.

We shall now define the various forms of metamorphic argillaceous rocks, often spoken of as pelitic :

Phyllite is a foliated rock of clay composition, shining with finely crystalline muscovite and chlorite. It is more crystalline, and therefore more lustrous, than slate.

Mica-schist is a foliated rock, generally of clay composition and medium texture, and always rich in mica, which typically includes biotite.

Garnetiferous mica-schist is a highly metamorphosed mica-schist, which has developed garnet (Fig. 57). Common garnet is a ferromagnesian aluminium silicate of cubic crystallization.

The grade of metamorphism of a pelitic rock is fairly well indicated by the presence, or absence, of certain index minerals. Barrow and his disciples, working in the Scottish Highlands, have pointed out that the following serve as good indices : chlorite, biotite, garnet, staurolite, kyanite, sillimanite.

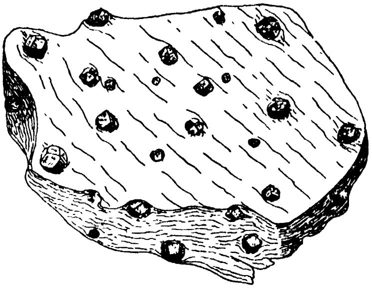

Fig. 57. Garnetiferous mica-schist.

The order given is the order of increasing metamorphism. A schist is said to belong to the biotite grade if it contains biotite and no garnet, and to the garnet grade if it contains garnet and no staurolite, and so on.

Regionally metamorphosed arenaceous rocks are often called psammitic. The following are types :

Quartzite may be mentioned, although many quartzites are merely cemented sandstones, and not metamorphosed in the true sense. A quartzite is a highly quartzose sandstone with quartz cement.

Quartz-schist is a quartzose rock with enough parallel mica to give a foliation.

Schistose grit is a grit which has developed foliation through earth movement. It is a very common type in the Southern Highlands.

Among calcareous rocks, regional metamorphism turns pure limestones into marbles, and impure limestones into calcareous schist, if there has been enough clay material to develop mica.

Among igneous rocks, regional metamorphism changes basalt and dolerite into hornblende-schist. The hornblende results from interaction between olivine and augite, on the one hand, and labradorite, on the other. A certain amount of plagioclase is always left. From granite it makes granite-gneiss with very little mineral change, but with a development of foliated structure.

Gneiss is a broad term. It means a coarsely crystalline foliated rock, which in typical cases has the minerals of a granite or a diorite.

Gneisses may result from the metamorphism of igneous rocks, in which case they are called orthogneisses. Or they may result from the metamorphism of sediments, in which case they are called paragneisses. It is generally easy to distinguish ortho- and para-gneisses, because, as already pointed out, igneous and sedimentary rocks have contrasted chemical compositions. Let us, for instance, compare an orthogneiss, that has resulted from the metamorphism of a granite, with a paragneiss, that has resulted from the metamorphism of a felspathic sandstone. Most sandstones are much richer in quartz, and therefore in SiO_2, than granites. By this test many specimens of Moine gneiss from the Scottish Highlands may be recognised as paragneiss. Or again compare an orthogneiss, that has resulted from the metamorphism of a basic igneous rock, with a paragneiss of similar SiO_2 percentage, which has resulted from metamorphism of a shale. The rules have already been given:

Usually in a basic igneous rock: $CaO > MgO$; $Na_2O > K_2O$; and molecularly $CaO + Na_2O + K_2O > Al_2O_3$.

Usually in a shale: $CaO < MgO$; $Na_2O < K_2O$; and molecularly $CaO + Na_2O + K_2O < Al_2O_3$.

Accordingly a chemical analysis almost always decides whether a metamorphic rock started as a basic igneous rock or a shale. Fortunately we need not as a rule go to the expense of a chemical analysis. An orthogneiss derived from basic igneous rock is almost certain to contain hornblende, which as we have seen is the Na-ferromagnesian silicate. A paragneiss derived from shale will probably be rich in biotite, which is the K-ferromagnesian silicate, rather than hornblende. In fact the outstanding feature of the paragneiss is likely to be an abundance of mica, black or white, since these minerals not only contain K, but are also rich in Al.

The statements offered above hold only for districts of straightforward regional metamorphism. In many cases regional metamorphism has been accompanied by igneous injection, and the products are mixed-rocks, for which the title migmatite is commonly employed.

PART III

CRYSTALLOGRAPHY

CHAPTER XXV

GENERAL CRYSTALLOGRAPHY

We have already defined a crystal as internally dissimilar in certain intersecting directions, though similar in all parallel directions (Chapter XII).

A crystal may be detected by its internal properties, and also by its external form, where it has grown under conditions that allow it to assume a characteristic shape.

Crystals generally grow from vapour, fusion or solution, conditions that give the atoms freedom to find their place in formations of regular pattern. Quick cooling of a silicate melt gives glass, with disordered atoms.

Faces of crystals grow parallel to themselves, and can, if needs be, repair themselves.

The general shape of a crystal is called its habit. A mineral like calcite may exhibit a great variety of habit according to conditions of growth. For instance it may be long and spiky, or short and stumpy.

Differences of habit may be due either to development of new faces or to differential growth of old faces.

LAW OF CONSTANT ANGLES.—In Nature, though not in models designed for beginners, the relative dimensions of corresponding faces vary ; but even in Nature the angles between corresponding faces are constant. This statement is really a repetition of what has just been said about a crystal face growing parallel to itself.

The measurement of interfacial angles is of fundamental importance in Crystallography, and is performed with an instrument called a goniometer (Greek for angle measurer).

You will remember that we can refer crystals to axes for purposes of description. Only three axes are necessary in any case ; and only three axes are used, except in the Hexagonal System. Let us limit our attention for the most part to the three-axis scheme.

The axes, as you know, are imaginary lines drawn through the crystal centre, each parallel to a crystal edge or to an axis of symmetry. If the crystal has the same properties along two or more axes, then these axes are said to be equal ; if it has different properties along any two axes, then these axes are said to be unequal. Finally, crystallographers, where possible, select axes at right angles and of equal length.

All this has already been explained. Now we want to go a little farther. The three axes are named A, B and C.

The A axis comes from the centre towards the observer, when the crystal is held in its standard position. The + end of the A axis lies towards the observer. The − end lies on the backward extension, on the other side of the centre.

The B axis extends right and left through the centre. Its + end is to the right ; its − end to the left.

The C axis extends vertically through the centre. Its + end is at the top ; its − end at the bottom.

When we give the measurements of crystal axes we are not concerned with actual lengths, but with relative lengths. We do not say that a crystal axis is so many feet or centimetres long ; instead we state a ratio, saying, for instance, that the A axis is a times as long as the B axis. In statements of axial length we always, for convenience, treat the length of the B axis as unity. This custom has some resemblance to that practised on the race-course, where, according to report, ratios are expressed in the form 2 : 1, rather than 46 : 23. In the Cubic System, where all three axes are equal, the ratio is 1 : 1 : 1. In the Tetragonal System, where only A and B are equal, the ratio is $1 : 1 : c$. In the Orthorhombic, Monoclinic, and Triclinic Systems, where all three axes are unequal, the ratio is $a : 1 : c$.

To measure the relative lengths of unequal axes, we choose as standard some face that cuts all three axes, and we take the ratio of its intercepts along these axes as fixing the axial ratio $a : 1 : c$. The intercepts are not measured directly, but are calculated from the values of interfacial angles measured with a goniometer.

LAW OF RATIONAL INDICES.—The procedure outlined above is important, because it has been discovered that a very simple relation connects the interaxial slopes of all faces belonging to one and the same crystal. The interaxial slopes of any face, if stated in terms of the axial lengths proper to the crystal, can be expressed in whole numbers. Three numbers are required. They are called indices, and are written in definite order : the first index refers primarily to the A axis, the second to the B axis, and the third to the C axis. Together they constitute what is called the Miller symbol of the face, in honour of their inventor Miller. Some authors write them inside simple brackets.

Let us build up the rule connecting interaxial slopes and indices in stages, so that we may easily visualize the relationships.

If the other two indices remain unaltered, then the interaxial slopes of a face towards a particular axis are proportional to the corresponding index.

Thus the face (011) has no slope towards the A axis ; in other words it is parallel with the A axis (Fig. 58).

Again the face (211) slopes towards the A axis, from the B and C axes, twice as steeply as the face (111) (Fig. 58).

The face (111) is the standard face, which we have already employed in measuring the axial ratio.

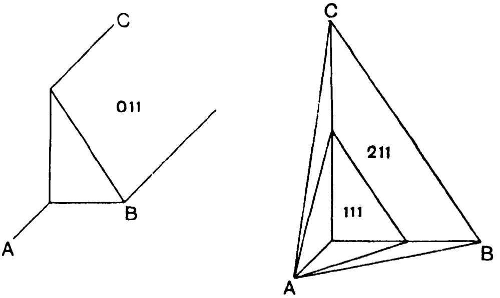

Fig. 58. Comparison of the interaxial slopes towards the A axis of the faces (011), (111) and (211).

We are now prepared for the full statement.

Let us take some face such as (432) as representative. The face (432) has a 4 in 3 slope towards the A axis from the B axis, a 3 in 2 slope towards the B axis from the C axis, and a 2 in 4 slope towards the C axis from the A axis—all measured in terms of axial lengths. That is, if we wish to draw a diagram showing the slope between the A and B axes, we mark two distances, 4 along the B axis and $3a$ along the A axis, and join the points thus obtained (Fig. 59, left).

This method of drawing interaxial slopes does not as a rule give us a picture of a crystal face. Thus in our diagram of the interaxial slopes of the face (432), the lines indicating the slopes 4 in 3 and 3 in 2 do not cut the B axis at the same point. The difficulty can be got over very simply. From the two ends of any one of the three slope-lines, draw lines parallel to the other two slope-lines; we then obtain the required picture of the face (432) (Fig. 59, right).

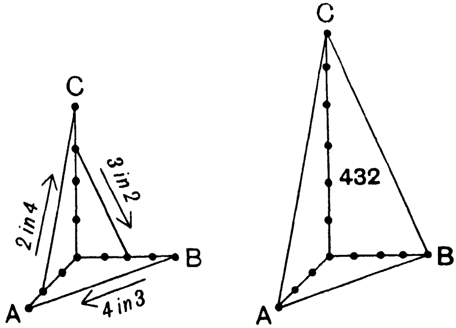

Fig. 59. On the left the interaxial slopes of the face (432) are plotted in the simplest manner possible. On the right they are combined to give a picture of the face.

The use of signs is very obvious. If a face cuts an axis on the + side, the corresponding index is +. If it cuts it on the − side, the index is −. To save room + signs are not expressed in the symbol, and − signs are placed above, instead of in front of, the index involved. Thus, in a cube (100) is the near face, and $(\bar{1}00)$ is the far face. Also, in an octahedron, (111) is the front right top face, and $(\bar{1}\bar{1}\bar{1})$ is the back left bottom face. It is easy to see that faces with opposite corresponding signs are parallel. Thus (111) is parallel to $(\bar{1}\bar{1}\bar{1})$ (Fig. 60).

The simple numerical symbols that define crystal faces are reminiscent of the simple numerical formulae that define chemical compounds, such as FeO, Fe_2O_3, Fe_3O_4. As a matter of fact the laws of Constant Angles and Rational Indices in Crystallography are closely analogous to the laws of Constant and Multiple Proportions in Chemistry. The crystallographic and chemical laws are alike dependent upon the atomic constitution of matter. Atoms are the ultimate bricks of which crystals are built, just as they are the ultimate particles of which compounds are composed. A crystal face is a plane that passes through the centres of a number of similar neighbouring atoms. The neighbours are soon used up, so there are not many faces possible to a crystal; and these faces are linked together by the simple geometry expressed in the law of Rational Indices.

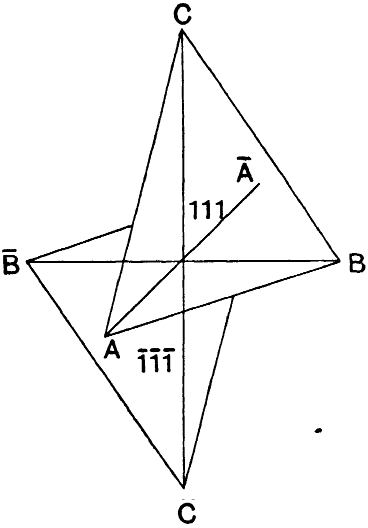

FIG. 60. Parallelism of the faces (111) and $(\bar{1}\bar{1}\bar{1})$.

The scientific idea of atoms came as a result of chemists using the balance. It might equally well have come as a result of crystallographers using the goniometer.

When we look sufficiently closely at crystal structure to think in terms of atomic spacing, we find that some of our previous statements require corresponding adjustment. It is no longer true that a crystal is internally similar in *all* parallel directions, but rather that the properties of a crystal along any one line are repeated exactly along a set of equispaced parallel lines that are separated from one another by distances of interatomic magnitude.

A crystal axis now becomes a line drawn through a series of equivalent atoms; and unit length along such an axis becomes a definite distance, namely that separating successive atoms.

All this has long been understood, but it only came within the province of measurable reality, in comparatively recent times, as a result of indirect observation with the help of X-rays. Nowadays we know the internal atomic pattern and the interatomic spacing of most mineral crystals.

As might be expected, the internal pattern of chemically complex crystals is influenced by the virtual size of their component atoms. This renders intelligible the isomorphism of albite, $NaAlSi_3O_8$, and anorthite, $CaAl_2Si_2O_8$, for it happens that Na has much the same atomic volume as Ca, and Al as Si. On the other hand albite is not isomorphous with, but only similar to, orthoclase, $KAlSi_3O_8$, because Na differs considerably from K in atomic volume.

SYMMETRY.—Let us drop this side of the subject for a little, and say a few words about symmetry.

Most crystals have a centre of symmetry, in the sense that each face is balanced by a parallel face on the other side of the crystal.

Many crystals have an axis of symmetry, that is, a line about which a crystal may be turned into more than one position of identical aspect during a complete revolution.

If identical aspect is reached twice during a complete revolution, the axis is said to be of twofold symmetry.

Similarly, if identical aspect is reached 3, 4, or 6 times, the axis is said to be of 3-fold, 4-fold or 6-fold symmetry, as the case may be.

It is interesting to note that there are no axes of 5-fold, 7-fold or higher symmetry. Such axes are possible in flowers, but not in crystals. The simplest proof that there cannot be an axis of 5-fold symmetry is based upon the atomic structure of matter. As a rule there is more than one sort of atom building up a crystal. In NaCl for instance there are two sorts, Na and Cl. In what follows we shall concentrate attention upon a single sort.

Mark a point *O* on a sheet of paper to represent the emergence of a hypothetical axis of 5-fold symmetry at right angles to the paper (Fig. 61). Then represent by a dot *a* the position of the atom which lies nearest to *O*, without actually coinciding with *O*. The 5-fold symmetry about the axis will determine the existence of a regular pentagon *abcde*, with similar atoms at each corner. The line *ac* will be parallel to the line *ed*. As the atom *a* is similar to the atom *e*, there must be an atom *f* along *ac*, where *af* = *ed*. But *Of* is less than *Oa*, which is impossible. Therefore an axis of 5-fold symmetry is impossible.

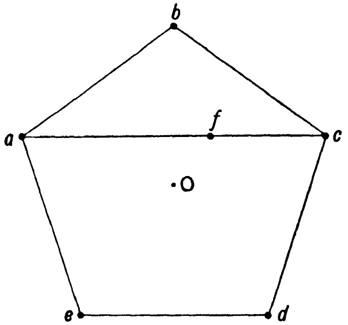

Fig. 61. Diagram illustrating the impossibility of a five-fold axis of symmetry in crystal structure.

Many crystals have a plane of symmetry, that is, a plane which divides a crystal into identical halves, the one the mirror image of the other.

We have already defined the six crystallographic systems in terms of crystallographic axes (Chapter XII). These systems include a number of classes, distinguished among themselves by minor differences of symmetry. The following statements in regard to elements of symmetry refer in each case to the most symmetrical class of the particular system named.

Cubic.	Centre	
	Three 4-fold axes	thirteen
	Four 3-fold axes	
	Six 2-fold axes	
	Nine planes	

TETRAGONAL.	Centre	
	One 4-fold axis	five
	Four 2-fold axes	
	Five planes	
ORTHORHOMBIC.	Centre	
	Three 2-fold axes	
	Three planes	
MONOCLINIC.	Centre	
	One 2-fold axis	
	One plane	
TRICLINIC.	Centre	
HEXAGONAL.	Centre	
	One 6-fold axis	seven
	Six 2-fold axes	
	Seven planes	

You will notice that in all except the Cubic System the axes and planes of symmetry are of equal number. This is because of a simple geometrical rule, that any even-fold axis of symmetry combined with a centre of symmetry must be accompanied by a plane of symmetry at right angles.

The rule does not hold for 3-fold axes. Therefore in the Cubic System there are four less planes than axes.

It would be hard to ask you to learn these lists by heart, even though it is difficult to forget that the six systems have either 0, 1, 3, 5, 7, or 9 planes of symmetry. Fortunately there is no need to commit anything to memory. Let us take a cube, for example, as representative of the Cubic System. Count its faces, there are six ; and its corners, there are eight ; and its edges, there are twelve. It is such a simple matter that one can do it with one's eyes closed. Now look at any cube face. Obviously a 4-fold axis emerges at its middle point. The same axis emerges at the middle point of the opposite face. Therefore there are half as many 4-fold axes as there are faces ; that gives three. Similarly a 3-fold axis runs through each pair of opposite corners ; that gives four. Similarly a 2-fold axis runs through the middle points of each pair of opposite edges ; that gives six. And as there are nine even-fold axes, there must be nine planes.

CHAPTER XXVI

FORMS OF THE CUBIC SYSTEM

Now that we understand about symmetry we can define a very useful term namely form.

A form is a set of similar faces linked together by symmetry.

The symbol of a form is the symbol of a constituent face, put inside some particular type of brackets. Thus if the symbol (321) means one face, then {321} means a number of faces, linked together by the symmetry of the particular crystal concerned. Some authors use 321 for face, and (321) for form.

In crystals with a centre of symmetry, the simplest possible form consists of two parallel faces. That is the form {321} must contain the face $(\bar{3}\bar{2}\bar{1})$ as well as the face (321). A form which consists merely of two parallel faces is called a pinacoid, and cannot by itself enclose a crystal. It is an open form.

There are many other forms, such as prisms, domes and bipyramids, found in various systems. The present chapter is limited to a discussion of comparatively complex forms found only in the Cubic System, because if you understand them you can easily master the forms of less symmetrical systems.

The Cubic System has so many elements of symmetry that all its forms consist of six or more faces, capable of completely enclosing a crystal. All the Cubic forms are closed forms. Also in any form such as {321} symmetry ensures that every face shall occur which contains the indices 3, 2, and 1, positive or negative, in any arrangement. Thus without thinking we know that {321} must have a face $(1\bar{2}\bar{3})$. There are, in all, forty-eight such faces ; but the number is reduced if two or three indices are equal, or if any index is 0. In the extreme case, the cube {100}, there are only six faces.

We can get representative examples of the Cubic forms by using the indices 0, 1, 2 and 3, combined in groups of three to give Miller symbols. There are seven representative forms, three with 0 in their symbols, {100}, {110}, {210}, and four without, {111}, {211} {221}, {321}. Forms with 0 in their symbols have some vertical faces, and forms without 0 have none. Our rule connecting indices and interaxial slopes tells us that in any form :

The biggest index of a face symbol shows the axis-end from which the face starts. The smallest index shows the axis-end to which the face points least.

Thus (321) starts from the *A* axis-end, and points more to the *B* than to the *C* axis-end.

Similarly $(1\bar{3}2)$ starts at the $\bar{B}$ axis-end, and points more to the *C* than to the *A* axis-end. This rule is easily modified to meet special cases, where any or all of the indices are equal.

Let us consider three categories :

(1) In forms with one index bigger than the other two, each face starts from only one axis-end. Such forms are {321}, {211}, {210}, {100}.

(2) In forms with two equal indices bigger than the third, each face is shared by two axis-ends. Such forms are {221}, {110}.

(3) In the one form with three equal indices, each face is shared by three axis-ends. This form is {111}.

There are six precisely similar axis-ends in the Cubic System. Therefore forms of group (1) must have a total of six times as many faces as meet at any one axis-end ; forms of group (2) must have three times this number ; and forms of group (3), two times.

The number of faces that meet at the *A* axis-end is easy to decide in any particular form. Let us take the most general {321}.

To begin with, let us make a head-on drawing facing the *A* axis (such drawings are best made on squared paper). This axis will be represented by a point *A*, the other two axes by horizontal and vertical lines through *A*. Let us think for a minute of the face of a cube. Evidently the horizontal and vertical lines we have drawn to represent the *B* and *C* axes will equally well represent the horizontal and vertical planes of symmetry that intersect in the axis *A*. Now let us draw two additional lines through *A* to bisect our four right angles. These will represent the diagonal planes of symmetry that intersect in the axis *A*.

We now have eight equal angles meeting at *A*. Each of these represents in our picture the angle of a face belonging to our general form {321}, because it is impossible for faces of this form to pass a plane of symmetry without being reflected, as it were, into a new face (Fig. 62).

It is the easiest matter in the world to give symbols to these faces : each must begin with 3, as each starts from the $+A$ axis-end ; those that lie nearest to the $+B$ axis-end must have 2 in the second place ; and so on. Starting in the first angle above the $+B$ axis, we have (321) ; and proceeding counterclockwise from this beginning we have in all 8 faces : (321) ; (312) ; $(3\bar{1}2)$; $(3\bar{2}1)$; $(3\bar{2}\bar{1})$; $(3\bar{1}\bar{2})$; $(31\bar{2})$; $(32\bar{1})$. It is very good practice to do this simple problem and ponder over the result.

In most other forms, fewer faces than 8 meet at *A*. The principles are so simple that they merely require understanding, not memory. Start as before by drawing the four planes of symmetry passing through *A*. If a face points directly along a plane of symmetry it will not have an edge in that plane. Take three examples (Fig. 62) :

The face (210) of the form {210} starts at *A* and points directly at *B* because the 0 tells us it does not point at *C* at all. Therefore it points directly along the horizontal plane of symmetry. Therefore the form {210} has no edge in this plane, but it does have edges in the diagonal planes.

The face (211) of the form {211} starts at *A* and points equally at *B* and *C*. Therefore it points directly along the diagonal plane of symmetry between *B* and *C*. Therefore the form {211} has no edge in this plane, but it does have edges in the horizontal and vertical planes.

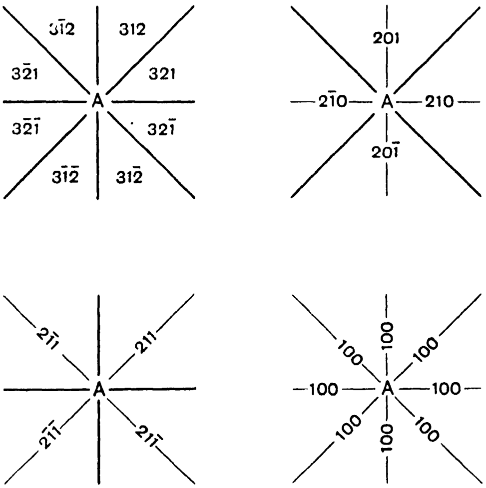

FIG. 62. Cubic Forms. Head-on drawings of the meeting of faces in the A axis. Thick lines are edges ; thin lines are planes of symmetry not occupied by edges.

The face (100) of the form {100} fulfils both conditions. It has 0 in its symbol, so that {100} has no edges in the horizontal and vertical planes through *A*. Also (100) points equally, namely not at all, at *B* and *C*, so that {100} has no edges in the diagonal planes through *A*.

We have got a long way with a head-on drawing of any form, once we have inserted the faces that start from the *A* axis-end. We have already seen that the symbols tell us whether these faces reach the other axis-ends, or are interrupted by edges. Let us see that we understand by taking each representative form in turn. We begin by drawing faint vertical, horizontal and diagonal construction lines. Then according to the principles just explained, we can insert the faces that meet the *A* axis-end and the intervening edges.

The first three forms (Fig. 63) have 0 in their symbol. They therefore have some faces that are parallel to the *A* axis. Such faces will be represented by lines in our head-on drawings.

{100} CUBE.—Only one face (100) meets the *A* axis-end. The corresponding face at the *B* axis-end is (010), which obviously is represented in our drawing by a vertical line, the edge in which it meets (100). As *A* is an axis of 4-fold symmetry, there will be three other edges completing a square about (100). Thus our drawing shows (100) as a square, and four faces (010), (001), (01̄0) and (001̄) as lines; while one face (1̄00) is hidden. This gives a total of six.

{110} DODECAHEDRON.—We can at once put in four faces (110), (101), (11̄0), (101̄) starting from the *A* axis-end and separated by edges in the diagonal planes. Let us consider (110) more particularly. Obviously it reaches the *B* axis-end. To complete our drawing of (110) we complete the square with *A* and *B* at opposite corners. To complete our drawing of the whole form, we complete the other three faces in like manner. Our drawing shows four faces beginning with 1 as squares, and four faces beginning with 0 as lines—obviously the line *BC* represents the face (011); while four faces beginning with 1̄ are hidden. In all there are 12 faces. The Greek *dodecahedron* means 12-faced figure.

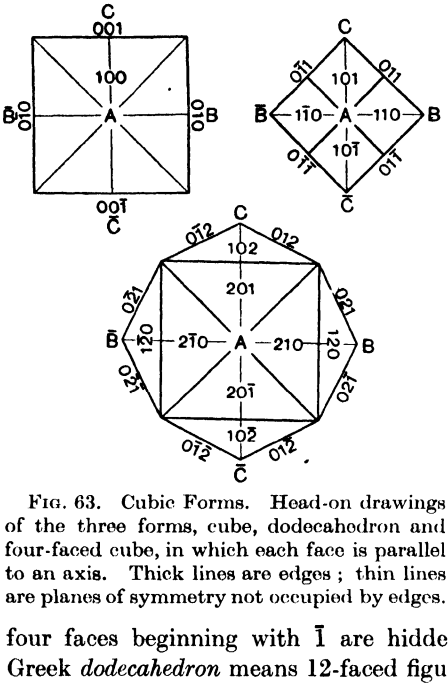

FIG. 63. Cubic Forms. Head-on drawings of the three forms, cube, dodecahedron and four-faced cube, in which each face is parallel to an axis. Thick lines are edges; thin lines are planes of symmetry not occupied by edges.

{210} FOUR-FACED CUBE.—We can place four faces (210), (201), (21̄0), (201̄) starting from the *A* axis-end and separated by edges in the diagonal planes. At this initial stage our drawing resembles {110}; but the face (210) cannot reach the *B* axis-end. It must meet in this direction (120). As both (210) and (120) are parallel with the *C* axis, they will meet in a vertical edge. This vertical edge, repeated by the 4-fold symmetry of the *A* axis, gives a square in our drawing, upon which stands a pyramid with four triangular faces (210), etc., all meeting in the *A* axis. Similar pyramids must meet in the other axes. The pyramid that meets in the *B* axis will be made of the faces (120), (021), (021̄) and (1̄20). Of these (120) will show in our drawing as a triangle, and (021) and (021̄) as lines, while (1̄20) will be hidden. It is easy to draw the lines representing (021) and (021̄) because they have a

2 in 1 slope towards the *B* axis from the + and − directions of the *C* axis. Our drawing so obviously represents a four-faced cube, that we realise without counting that the form has twenty-four faces.

The next four forms (Fig. 64) do not contain 0 in their symbol. They therefore have no face that is parallel with the *A* axis. Accordingly in these forms no face is represented in our head-on drawing by a line; every face is represented by an area, or else is completely hidden. Thus to count the faces of the form, we count the faces that are visible in the drawing and multiply by two.

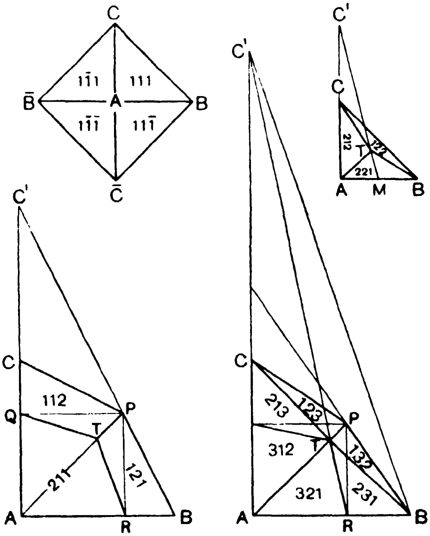

FIG. 64. Cubic Forms. Head-on drawings, mostly partial, of the four forms, octahedron, three-faced octahedron, icositetrahedron, and six-faced octahedron, in which no face is parallel to an axis. Thick lines are edges; thin lines are construction lines for the purposes of drawing.

{111} OCTAHEDRON.—We insert the four faces (111), $(1\bar{1}1)$, $(1\bar{1}\bar{1})$, $(11\bar{1})$ that meet in the *A* axis-end, separated by edges in the horizontal and vertical planes. The face (111) reaches from the *A* to the *B* and *C* axis-ends, so that it is represented by the triangle *ABC*. The drawing of the form is completed by completing the square $BC\bar{B}\bar{C}$. Four faces are seen, so that the form has eight in all.

{221} THREE-FACED OCTAHEDRON.—Eight faces (221), (212), etc. meet the *A* axis-end, separated from one another by edges in the horizontal, vertical and diagonal planes. The face (221) reaches from *A* to *B*, so that *AB* represents a single crystal edge. Symmetry at once tells us that *BC* and *CA* must also represent edges, and that there must be a face (122) on *BC* meeting (221) and (212) at *T*, the emergence of the 3-fold axis of symmetry. *T* of course lies on the diagonal plane of symmetry through *A*. For many purposes it is enough to insert it approximately by eye, and complete the drawing by joining *TA*, *TB* and *TC*. (If we want to fix *T* accurately, we can bisect *AB* at *M*, and join *M* to *C'*, where $AC' = 2AC$. *C'* is the point in which (221), if produced, would meet the *C* axis, so that *MC'* is the trace of the median in this face symmetrical with regard to *A* and *B*. *T* lies in our drawing at the intersection of *MC'* and the diagonal plane *AT*.) Our figure is evidently a three-faced octahedron, with twenty-four faces in all.

{211} ICOSITETRAHEDRON.—In this form only four faces (211), $(2\bar{1}1)$, $(2\bar{1}\bar{1})$, $(21\bar{1})$, meet at the *A* axis-end, separated from one another by edges in the horizontal and vertical planes. The face (211) will not reach the *B* and *C* axis-ends, so that at these ends we mark (121) and (112). The edge of 121 in the *BC* plane is easily drawn for it has a 2 in 1 slope towards *B*. Where this edge *BP* meets the diagonal plane of symmetry through *A*, it is reflected into *PC*, the corresponding edge of (112). Since the *C* and *B* axes are of 4-fold symmetry, *Q*, the corner in which (112) and (211) meet in the *AC* plane, will be at the same horizontal level as *P*. Similarly, *R*, in which (121) and (211) meet in *AB*, will in our drawing fall vertically below *P*. Three edges are now required, *PT*, *QT*, and *RT*, where *T* marks the emergence of the axis of 3-fold symmetry in the diagonal plane. As before, *T* may be inserted roughly by eye. (If we want it accurately we draw *RT* at such an angle that it will meet *BP* produced in the *C* axis.) Clearly our form is a variety of three-faced octahedron ; but, as this name is in use for {221}, the name icositetrahedron is here employed. It is Greek for 24-faced figure.

{321} SIX-FACED OCTAHEDRON.—The sketch of {211} can be roughly changed to represent {321} by inserting edges connecting *TA*, *TB*, and *TC*, and lettering the faces accordingly. (For accurate drawing *P* can be fixed by drawing *BP* with a 3 in 2 slope towards *B*. *R* falls vertically below *P*. Then find *C'*, the point in which (231), if produced, would meet the *C* axis. The crossing of *C'R* and *AP* gives *T*.)

The head-on drawings just described are very satisfactory except in the case of {100}, (110} and {111}. For these forms slightly oblique drawings are preferable (Fig. 65). The following are simple rules for obtaining such drawings without troubling about accuracy of detail.

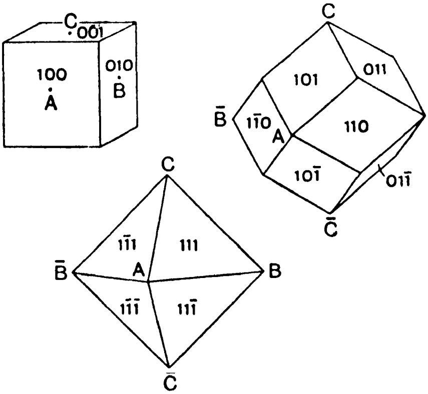

FIG. 65. Cubic Forms. Approximate oblique drawings of cube, dodecahedron and octahedron.

{100} CUBE.—Draw the square (100) and then indicate freehand the right hand face (010) and the top face (001) as seen obliquely. Any child knows how.

{110} DODECAHEDRON.—Draw a square faintly as a guide. Mark in the corners firmly. Place *A* a little below, and to the left of, the centre of the square. Join *A* to the four corners of the square. Complete the four parallelograms that meet at *A*. Complete the two parallelograms necessary to get rid of re-entrant angles. A very satisfactory dodecahedron emerges with six of its twelve faces in view.

{111} OCTAHEDRON.—Draw a square with its opposite corners placed horizontal and vertical. Place *A* a little below, and to the left of, the centre of the square. Join *A* to the four corners of the square.

The other forms can also be drawn obliquely, but there is not much artistic advantage.

PART IV

MICROSCOPIC EXAMINATION OF ROCKS AND MINERALS

CHAPTER XXVII

MINERAL SHAPE, CLEAVAGE AND COLOUR

MODERN geologists obtain a great deal of information from the microscopic examination of rock slices. The practice was introduced by an Englishman, Sorby, who died only a few years ago. During his lifetime the microscopic study of rocks came to be the main foundation of the branch of Geology known as Petrology. The descriptive side of Petrology is often called Petrography.

A chip of rock is ground and polished by rubbing on a revolving horizontal steel disc, covered successively with carborundum of two grades, and finally on a glass plate with still finer carborundum. It is next mounted on a glass slide, with its smooth face fixed to the glass with the help of Canada balsam. The rough face is then ground down in like manner, until almost all the constituents of the slice become transparent (the thickness is checked by examination between crossed nicols, a matter that you will understand presently). Finally the thin slice, covered and surrounded with Canada balsam, is protected with a cover-glass. It is then ready for examination with a microscope, just as if it were a botanical or zoological preparation. Such thin rock slices are being made every day in university laboratories (Figs. 36-40).

The constituent minerals of a rock slice are cut across at random. We have already seen that the properties of minerals vary according to direction ; and this must be constantly borne in mind when we are examining rocks and minerals under the microscope. Let us take two simple illustrations.

(1) Suppose we look at a slice of a quartz-porphyry, in which the quartz phenocrysts are hexagonal prisms with pyramid terminations. The random sections of quartz phenocrysts will have different shapes. Longitudinal sections will be long, with two parallel sides and pointed ends. Cross-sections will be regular hexagons. So we learn that the shape of a quartz crystal section varies according to direction. This introduces a difficulty, for how are we to know that the different sections are all quartz, if they do not have the same shape? After all, this is a familiar difficulty. When we look at a flock of sheep, some head on, some side on, some tail on, we see many different shapes ; but we have got accustomed to the complication, and we do not require any one to tell us that we are looking at one kind

of animal in different aspects. Thus in a slice of quartz-porphyry, the quartzes give intermediate, as well as long and short sections ; and all of them are clear, colourless and devoid of cleavage. To leave quartz, a question naturally arises as to whether we can determine the crystal system of a mineral from the shapes of a number of haphazard sections. If idiomorphic crystals show a tendency to give elongated sections, they are probably not Cubic. Cubic minerals have so much symmetry that their sections are generally as broad as they are long—examples : magnetite, pyrites, garnet. There are certain ill-fed crystals, called skeletons, that grow in curious elongated forms. Magnetite sometimes builds skeletons, but most of the magnetite that you will see with the microscope is in compact octahedra. Crystals of the Hexagonal System tend to give hexagonal cross-sections—example, quartz.

(2) Let us now turn from shape to cleavage. Many minerals, as we have already seen, have a characteristic cleavage or cleavages. Under the microscope a cleavage shows as parallel straight cracks. The relation between cleavage and direction is just as striking as that between shape and direction. Suppose we are looking at a slice of granite, we are certain to see sections of mica. Mica has one perfect cleavage, and most haphazard sections of mica show this clearly by one set of parallel cracks. A few sections perhaps may be cut parallel to this cleavage, in which case the cracks will not show, just as the pages of a book do not show when one looks down on the cover. This explains a puzzle. If you take a flake of mica and mount it as a microscopic slide, you must not expect to see the cleavage as parallel lines of cracks.

Let us now say a few things about cleavage as a help to identifying minerals in haphazard sections.

(*a*) A mineral that has no cleavage naturally cannot show cleavage in any section—examples : quartz and garnet. An absence of cleavage cracks is one of the most useful tests for distinguishing quartz from felspar—*cf.* Fig. 38B.

(*b*) A mineral that has only one cleavage cannot show more than one cleavage in any section, but it may show no cleavage at all in certain sections. Micas and chlorite are the only common minerals with a single cleavage, and this serves to distinguish them from groups (1) and (3)—*cf.* biotite, Fig. 38A.

(*c*) A mineral with two or more intersecting cleavages may show intersecting cleavage cracks in many sections, and in others may merely show one set of parallel cleavage cracks. It cannot show an uncleaved section, except by accident or where the cleavage is poor. Most rock-forming minerals have two or more cleavages—*cf.* augite, Figs. 37A-C, felspar, Figs. 37A, 38B).

We have already learnt that the cleavage angle of hornblende is about 60°, and of augite about 90° (Fig. 30). This is a very useful test for distinguishing the two minerals under the microscope. But it must be remembered that the cleavage angle, as seen in a haphazard section of hornblende, is not likely to be 60°. If the section is parallel to the length of the hornblende prism, the cleavage traces will be parallel to one another. It is only in a section at right angles to the prism that the cleavage cracks will be seen making approximately 60° with one another. Haphazard hornblende sections give any angle between 0° and about 60°. Similarly haphazard augite sections give any angle between 0° and nearly 90°.

We may now say a few words about colour in thin section.

Minerals with metallic lustre are opaque—examples : magnetite, pyrites. Their colour may be examined in reflected light.

Ferromagnesian silicates are transparent and coloured—examples : biotite, hornblende, augite. Olivine and garnet, however, are very pale.

Non-ferromagnesian silicates and quartz are transparent and colourless—examples : muscovite, felspars, quartz.

Susceptibility to decomposition is another useful criterion. Thus felspar is commonly clouded by secondary products, as seen in microsection, while quartz is clear—*cf.* Fig. 38A, B.

Up to this point we have been talking of properties that are visible with any microscope. The petrological microscope is always fitted with special pieces of apparatus called nicols, after their inventor, Nicol of Edinburgh.

For most purposes we may picture light as a wave-motion propagated through the ether. Vibrations take place in the wave front at right angles to the line of propagation, that is to the ray of light. Think of any horizontal ray of ordinary light. The vibrations may be up and down, or sideways, or any combination of up and down and sideways.

A nicol is an apparatus which will only transmit light that is vibrating in one particular direction. If we put a nicol in the way of a beam of ordinary light it will only let half the light through, and that half will be vibrating in the vibration-direction of the nicol. Such light is said to be polarised.

In a petrological microscope one nicol can be moved into position under the stage that carries the thin section ; and the other nicol can be moved into position above this stage. The lower nicol is called the polariser. The upper nicol is called the analyser. The polariser and analyser are mounted with their vibration-directions at right angles. They are therefore said to be crossed. Cross-wires are put in the microscope to mark the vibration-directions of the two nicols.

Let us now make a simple test with polariser in and analyser out.

The colour of biotite and hornblende is generally much affected by inserting the polariser. Moreover the colour of an individual section alters when it is rotated above the polariser. For instance, if a biotite section shows cleavage, its colour will be darkest when the cleavage is along one cross-wire, and palest when it has been rotated through 90° so that the cleavage lies along the other cross-wire. This property of changing colour on rotation in polarised light is called pleochroism. Like so many other properties it depends partly upon the mineral, and partly upon the direction. Colourless minerals are of course non-pleochroic. Among the coloured minerals that you are likely to meet, only biotite and hornblende are markedly pleochroic. But do not be surprised to find a few biotite and hornblende sections that do not show pleochroism. For instance, a biotite flake that does not show cleavage will not show pleochroism.

The pleochroism of a biotite flake that shows cleavage may be used to determine the vibration direction of the polariser. It is a rule that is useful to remember that biotite in its darker position is lying parallel with the vibration direction of the polariser. Hornblende gives its darker pleochroism when it makes a small angle with this vibration direction. Tourmaline, on the other hand, gives its darker pleochroism when it lies at right angles to the vibration direction of the polariser—a fact that constitutes a very convenient test for the discrimination of tourmaline.

CHAPTER XXVIII

REFRINGENCE AND BIREFRINGENCE

LET us turn to another optical property, namely refractive index. In Physics, refractive index is connected with the bending of light, which so often occurs where a ray passes from one transparent medium to another. In Petrology, refractive index has proved of immense value in the identification of material in rock slices. As we shall presently see, it is an easy matter to determine which of two transparent substances, lying side by side in a rock section, has the higher refractive index. Accordingly, if we start by knowing the one substance, so that we can look up its refractive index in a table, we acquire considerable evidence regarding the refractive index of the other substance, sufficient to help greatly in its recognition.

Comparison of refractive indices is often made in ordinary light, that is with both polariser and analyser withdrawn. An important thing to remember is that refractive index tests are most successful with the iris diaphragm moderately closed. The iris diaphragm is an apparatus intended to limit the hole through which light enters the microscope, much as the iris of one's eye limits the pupil. It is placed below the stage, and you must find it and learn how to use it. To make the actual comparison we perform what is called the Becke test, named after a great Viennese professor who discovered it. When you look with a microscope at an edge separating two transparent substances you will see that a narrow bright line runs roughly along the margin. This bright line may be exactly along the margin, or it may be on the one side or the other. Its position alters in this respect as the microscope is focussed up and down. Its movements tell us at once which of the two substances has the higher refractive index. Becke's rule is: Focus down and the bright line travels from high refractive index to low.

Nothing could be easier to remember, and few tests are more used by a petrologist.

Two remarks may be offered:

(1) It is almost always possible to find a contact between some particular mineral and the balsam surrounding a rock slice. Orthoclase, microcline and albite are the only very common minerals which have a refractive index less than that of balsam. Glass, such as you see in slices of pitchstone, also has a refractive index less than balsam.

(2) The bright-line effect increases in intensity as the difference in refractive indices increases. In keeping with this we find that minerals with a refractive index much higher than that of Canada balsam stand out prominently in a rock slice. Olivine is a case in point.

Refractive index is very often influenced by insertion of the polariser. Here is an important experiment that you can make to illustrate this point. Insert the polariser and examine the contact of a quartz crystal with balsam, say at the edge of a slice of granite. Rotate the slice into a number of positions, and in each try the Becke test. You are almost certain to find that in one position the refractive index of the quartz is nearly equal to that of the balsam, and that in other positions, especially in a position at right angles to the first, the refractive index is very distinctly higher.

Similar variation of refractive index is a commonplace in crystal sections; and if it occurs at all, then there are always two positions at right angles, for which the difference of refractive index is most clearly marked. Sections, in which the refractive index varies with rotation, are said to be birefringent; whereas sections, in which the refractive index remains unchanged during rotation, are said to be isotropic. By a series of experiments (but it is not advisable for you to spend time on making them) it can be shown that sections of non-crystalline substances, such as glass and Canada balsam, and also sections of Cubic crystals are isotropic; while most sections of crystals that are not Cubic are birefringent. Let us remember these facts, even though we do not bother with the experiment.

Where birefringence is very strong there may be no need of a microscope to realise it. If you look through any large clear calcite crystal, you will find that its birefringence makes you see double. As petrologists, however, we are only concerned with birefringence viewed through a microscope The distinction between isotropic and birefringent sections is much more easily recognised between crossed nicols than by the Becke test. You will remember that a nicol will only transmit light with a definite vibration-direction. Accordingly, crossed nicols, having their vibration-directions placed at right angles to one another, will not transmit light, unless something is put in between the nicols which modifies the vibration direction of the light from the polariser before it reaches the analyser. Experiment soon shows that isotropic substances, such as glass, Canada balsam and crystals of the Cubic System, have no tendency to modify the vibration direction of polarised light. When placed between crossed nicols such substances cannot be seen through the analyser. On the other hand birefringent sections do as a rule modify the vibration direction of polarised light; and when placed between crossed nicols they can be clearly seen through the analyser.

The following is a very simple and very instructive experiment. Rotate a birefringent section between crossed nicols. As it goes round it becomes black four times in a complete revolution. These four positions are along two lines at right angles to one another and are called extinction positions. In different minerals the extinction positions often have different relations to the length of the crystal section, or to the direction of its cleavage cracks. Let us consider two examples :

(1) An elongated section of biotite always extinguishes when its length is rotated into parallelism with either of the cross-wires of the eye-piece. Biotite is therefore said to have straight extinction.

(2) An elongated section of hornblende has almost always to be rotated so that its length is oblique to both cross-wires before it extinguishes. Hornblende is therefore said to have oblique extinction.

There is no time to elaborate these important properties ; you must learn their uses while working with slices in the laboratory. Here, however, is a warning. You must not expect that all haphazard sections of a mineral such as hornblende will give oblique extinction. As a matter of fact elongated hornblende crystal sections may give any angle of extinction from 0° to 20°, according to their orientation. Similarly, elongated crystals of augite may give any angle from 0° to 45°. It is the maximum extinction angles that are tabulated in reference books for the various minerals.

Though it is easy to distinguish birefringent minerals from isotropic minerals, glass, etc., between crossed nicols, the theory of the matter would take too long to explain in the present pages. Those of you who are going on with Geology should read it in more elaborate text-books—it is really very simple. Here it need only be pointed out that there are three factors concerned in the modification of the vibration direction of polarised light passing through a crystal section :

(1) The strength of the birefringence of the crystal as cut in the particular section ;
(2) the thickness of the section ;
(3) the wave-length of the light.

As light of different colours has different wave-lengths, the third factor determines that different colours are differently affected. White light is a mixture of all colours, so that the various ingredients of a white polarised beam are differently affected by a crystal section, and in turn differently transmitted by the analyser above. The principle may be illustrated by considering a very simple example. Suppose that a mixture of red and blue light has been transmitted by the polariser. Suppose also, as may quite well happen, that the vibration direction of the red light has been turned through 90° on passing through a crystal section, while that of the blue light has been turned through 180°. Obviously the red portion of the original mixture of lights will be passed by the analyser, and the blue part rejected. Accordingly the mineral section will appear red when viewed through the analyser. In illumination with white light, complex combinations of colours will result, depending upon the birefringence and the thickness of the section. These colours have been studied and, broadly speaking, may be summarized as follows for a section of standard thickness : black indicates zero birefringence; grey or white, low birefringence ; and bright colours, such as red or blue, high birefringence. Fuller details will be given in Chapter XXIX. Meanwhile a few obvious applications of microscopic examination may be noted.

In connection with the plagioclase felspars twinning has already been defined as a regular intergrowth of individual crystals of one species. The individual crystals that are intergrown are called twins. Often only two twins occur in association, in which case they are called simple. In other cases many twins are associated, in which case they are called multiple.

Excellent examples of simple and multiple twinning are afforded by the felspars. Orthoclase is prone to simple twinning, and plagioclase to multiple, combined with simple, twinning. You will remember that if you look at a cleavage face of a hand specimen of plagioclase you may see a succession of stripes of alternately different orientation, so that, for any particular position, one set of stripes may glitter while the other is dull. Twinning is generally much clearer between crossed nicols than in a hand specimen. As adjacent twins have different orientations they usually have different extinction positions and different polarisation colours. Thus multiple twins of plagioclase between crossed nicols show as alternating bands of two different colours or shades (Fig. 66). This is one of the most characteristic features of plagioclase, and helps greatly in its identification.

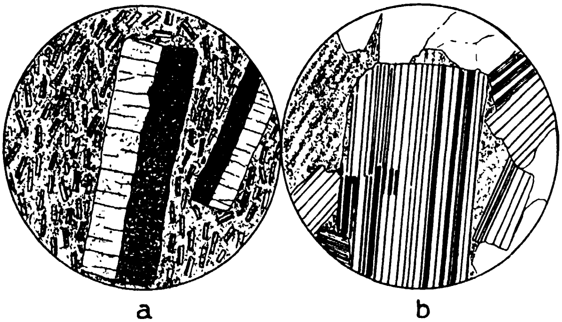

FIG. 66. Micro-sections between crossed nicols.
(a) Simple twinning in orthoclase.
(b) Multiple twinning in plagioclase.

As regards distinguishing the various types of plagioclase, a beginner should rely mainly on the Becke test. If the refractive indices are below balsam, the plagioclase is albite ; if very near balsam, in some sections below, in others above, the plagioclase is oligoclase. More calcic plagioclases have increasingly high refractive index. Often a plagioclase crystal has been built up in a series of zones. Its interior may be a kernel of labradorite, and its outer zones andesine, oligoclase and albite, in turn. The zones are easily recognised by differences of extinction angles between crossed nicols; and it is an instructive exercise to compare their refractive indices with that of balsam if a contact happens to be present in the slice.

The Becke test is of great assistance in the ancient art of prospecting brought up to date. Rivers, especially in non-glaciated countries, collect very useful samples of the valuable minerals of a country. Suppose, for instance, some river sand contains gold; by the help of this clue we may follow up the tributary, which supplies the gold, and eventually come to the vein, or reef, as it is often called. Most valuable minerals are heavy, and it is on this account that the natural washing by rivers tends to furnish concentrates. The prospector continues the washing process with his pan. Some of the valuable material that he looks for is opaque, and there are various physical and chemical tests for it, such as colour for gold, magnetism for magnetite, and blowpipe tests in other cases. The transparent material can be separated with heavy liquids. Broadly speaking, any transparent material that sinks in a liquid which floats quartz is worth considering, though of course it is more likely to be valueless than valuable. One of the chief tests of minerals thus sorted out into a heavy residue is based on the Becke test. A number of oils of known refractive index are kept in bottles (and periodically tested). The mineral powder is examined on microscope slides, on which it is mounted in turn in a drop of each of the standard oils. Becke's test shows that the mean refractive index (without polariser) of the powder is above that of one standard oil, and below that of the next. This is likely to identify the mineral, when reference is made to a list of minerals tabulated according to their refractive indices.

CHAPTER XXIX

MORE ADVANCED PETROGRAPHICAL TECHNIQUE

A STUDENT reading this book is expected to be learning much of his lesson in the laboratory. An average first-year student has neither time, nor apparatus, to go far with microscopic petrography. He should, however, become familiar with the commoner rock-forming minerals, and with the main textural varieties of rocks themselves. He should be able to read some of the history of a rock from its microscopical appearance. He should know how to distinguish a sedimentary from an igneous rock ; and in an igneous rock he should recognise signs of rapid or slow crystallization, and form some idea concerning the order in which the mineral constituents have consolidated.

A helpful start in getting to recognise minerals under the microscope is furnished by an examination of slices of those two most abundant of igneous rocks, granite and basalt (Figs. 37, 38). The student knows what to expect in such slices, and that is more than half the battle. With patience and occasional personal assistance, he should soon learn, on the basis of the two previous chapters, to recognise quartz, orthoclase, biotite (probably also muscovite and hornblende), plagioclase, augite, olivine and magnetite.

Here we have reached about the limit for the ordinary beginner. The remainder of the present chapter is really intended for second-year students. It furnishes additional material for the determination of birefringent minerals. It should greatly assist in the use of petrographic tables, which are arranged in key form to guide in the recognition of any mineral that can reasonably be expected to occur in a rock slice. A student who feels at home with a petrographic table has established himself in a self-reliant position.

One excuse for introducing moderately advanced technique into an elementary treatise is that beginners are apt to find existing accounts rather difficult to follow (but see H. H. Read, *Rutley's Elements of Mineralogy*, 23rd ed., 1936, chap. iv, which has appeared since this chapter was prepared).

TO CENTRE OBJECT GLASS.—It is often necessary to rotate a small crystal section in the centre of the field of a high-power objective. For this purpose accurate centring is essential. The procedure is as follows: Choose some minute crystal as a marker. Move it beneath the intersection of the cross-wires. Rotate the stage. If the axis of rotation coincides with the intersection of the cross-wires, rotation will leave the marker on this intersection.

If not, rotation will carry the marker away from the intersection to perform a small circle round the axis of rotation. Thus when the stage has been rotated through the 180°, the axis of rotation must lie at the midway point between the intersection of the cross-wires and the displaced position of the marker. Two screws, at right angles, are provided for the centring of the object glass, which latter carries with it the image of the cross-wires. With the help of these screws bring the image of the intersection of the cross-wires to coincide with the ascertained position of the axis of rotation.

Test as before ; and, if the centring is still imperfect, repeat the screw adjustment.

WEDGES AND PLATES.—For crossed-nicol work it is sometimes important to be able to reproduce a standard scale of colours, which corresponds with increasing birefringence. Accordingly a full petrographic outfit always contains a quartz-wedge. This is a long, narrow, very thin slip of quartz, mounted on glass, and cut to give straight extinction. The quartz is not of uniform thickness, but ground so as to taper regularly to a feather edge. When inserted in the 45° position with reference to the cross-wires (somewhere between the crossed nicols, either on the stage of the microscope, or in a slit provided in the microscope tube—try both), the quartz-wedge gives the requisite scale of colours. Starting from the taper edge we have the following succession : black, grey, white, yellow, red, violet, blue, green, yellow, etc. Several of the colours repeat so that we have yellow, for instance, of more than one order. The violet mentioned above is called the sensitive violet, and the colours disposed on the thin side of it are called first-order colours. The colours of successively higher orders show a tendency to merge, and towards the thicker end of the wedge are replaced by continuous white, spoken of as white of a high order. All this may seem to require a good deal of memory; but in actual practice the more significant facts can be acquired in a few educative minutes spent in manipulation of a quartz-wedge.

The quartz-wedge is supplemented by two other pieces of apparatus, called respectively a mica-plate and a gypsum (selenite)-plate. They consist of cleavage plates of uniform thickness, mounted to give straight extinction. Standard thicknesses are selected ; and an orthodox mica-plate in the 45° position between crossed nicols gives grey-white of the first order, while an orthodox gypsum-plate gives the sensitive violet.

HELPING AND HINDERING.—Now take a granite slice and fix your attention on some grain of quartz or felspar that is giving, say, white between crossed nicols. Rotate the slice until the grain is as bright as possible, that is, until its two extinction directions are in the 45° position as regards the cross-wires. Now gradually insert the quartz-wedge, first along the one extinction direction, then along the other. The effects are contrasted : in the one case the grain and quartz-wedge help one another and give a colour that is higher in the scale than either gives alone ; in the other case the two hinder one another, and when, for instance, either alone would give white, the two together give black, signifying complete compensation.

The above experiment is easy because the colour due to the quartz-wedge can be adjusted by using a thinner or a thicker part. Except for this, similar experiments can be made with the mica- and gypsum-plates. Here again it is very obvious that different effects are produced when either plate is inserted, first along the one, and then along the other, extinction direction ; but, as the plates are of uniform thickness, it is unlikely that their hindering effect will amount to exact compensation in conjunction with a haphazard grain.

A gypsum-plate is usually employed where very lowly birefringent grains, giving grey, have to be tested. The sensitive violet of a gypsum-plate is readily raised to blue by a helping grey, and lowered to yellow by a hindering grey.

THIN EDGES.—Sometimes it is easier to distinguish helping from hindering by attention to colour movement rather than colour change. Many sections of crystal grains are thinner at some portion of their margin than in their interior. If these thin edges are in contact with balsam or with a relatively lowly birefringent mineral, or even with a highly birefringent mineral in the extinction position, they will give a rim of colour lower in the scale than that due to the thicker interior. Any rock slice that is examined is likely to provide examples—for instance where remnants of olivine are surrounded by serpentine. The test is easy. Place the grain with its extinctions in the 45° position. Insert the quartz-wedge, first along one, then along the other extinction direction. Watch while the wedge travels in. If the colours migrate from the thick to the thin of the grain, the wedge is helping and vice versa.

Excellent practice can be obtained from calcite grains lying against balsam. Here the marginal colour bands are likely to be so narrow that their migration may only be visible under a high power.

X, Y, Z AXES.—Standard books and tables, in their accounts of Triclinic, Monoclinic and Orthorhombic minerals, list three principal refractive indices, corresponding with three vibration directions at right angles to one another : the three principal indices are called α, β and γ, beginning with the smallest (an order that is so natural that it is easy to remember) ; the three corresponding vibration directions are called X, Y and Z (or $\mathfrak{a}$, $\mathfrak{b}$ and $\mathfrak{c}$), and are spoken of as the principal axes of the optical indicatrix. The X, Y and Z axes need have no relation to the crystallographic axes, except in so far as the latter are axes of symmetry or stand at right angles to planes of symmetry. What we must fix in our minds is that X and Z are the vibration directions corresponding respectively with the smallest and largest refractive indices of the mineral concerned.

Where any one of the X, Y, Z axes lies in a section, it functions as an extinction direction. It is possible to have both the X and Z axes lying in one and the same section, in which case both function as extinction directions. Of course this relationship is exceptional, so that the strict X, Z terminology has few applications to haphazard birefringent sections.

X-ER AND Z-ER AXES.—By analogy it is justifiable to distinguish the two extinction directions of any birefringent section under the names X-er and Z-er axes, defined as follows: the X-er axis of a mineral section is the vibration direction corresponding with the smaller refractive index (probably not exactly α); and the Z-er axis is the vibration direction corresponding with the larger refractive index (probably not exactly γ). This terminology of X-er and Z-er can be applied to any birefringent crystal, no matter its system.

POSITIVE AND NEGATIVE.—A mineral is said to be + with respect to a particular direction if the X-er axis lies perpendicularly *across* that direction.

This definition is easy to remember because both the positive sign and the letter X are themselves crosses.

A mineral is said to be − with respect to a particular direction if the X-er axis lies *along* that direction.

SIGN OF A QUARTZ-WEDGE.—Let us begin by determining the sign of our quartz-wedge and mica- and gypsum-plates. This is easily done with the help of a thin slice of granite. The procedure is as follows:

(1) Determine the vibration direction of the polariser by noting the dark position of a pleochroic biotite (Chapter XXVII).

(2) Determine by the Becke test which extinction position of some selected grain of quartz gives the lower refractive index (with the analyser removed and the polariser left in position, Chapter XXVIII). The X-er axis of a grain that is orientated to give its lower index, must be lying parallel with the vibration direction of the polariser. Make a sketch of the grain, marking on the sketch the X-er axis. Rotate the slice through 45°. Insert the quartz-wedge at right angles to the X-er axis of the grain. If it helps, the quartz-wedge is +. If it hinders, it is −.

Once we have determined the sign of our instruments, we should label them, + or − as the case may be. We should of course test them, one against the other.

SIMPLE USE OF INSTRUMENTS.—Our marked instruments can be employed to determine the positive and negative directions of any mineral in a slice. Place the mineral with its extinction directions in the 45° position, and insert along one or other of these directions the testing wedge or plate. If the two help one another, their X-er axes are parallel; and vice versa.

A few simple experiments will satisfy a student that:

(1) Muscovite is + with regard to its cleavage.

(2) Idiomorphic quartz is + with regard to its length.

(3) Nepheline is − with regard to its prismatic cleavage, which often gives close parallel lines in sections that show the maximum birefringence of the mineral.

Biotite, owing to its colour, is a difficult subject. Sometimes it has a thin edge, which allows of the migration test.

ORDINARY AND EXTRAORDINARY INDICES.—So far as muscovite is concerned, the results just noted are easily confirmed in terms of the X phraseology by reference to books or tables. On the other hand these publications use a different terminology in the case of quartz and nepheline. In fact for the Hexagonal and Tetragonal systems, only two principal refractive indices are listed, ω the ordinary index, and ϵ the extraordinary. The ordinary index can be found in any section—it corresponds with vibrations along any direction in the plane at right angles to the principal axis of symmetry. The extraordinary index, in its full tabulated value, can only be found in exceptional sections that include the principal axis of symmetry—it corresponds with vibrations along this axis. In most birefringent sections the ordinary index, ω, is accompanied by an index intermediate in value between ω and ϵ.

We need find no difficulty in remembering that the vibration direction corresponding with the extraordinary index lies along the principal axis of symmetry. It is mere common sense that a unique vibration direction cannot make an angle with an axis of 6-fold, 4-fold or 3-fold symmetry.

Let us now consider the information tabulated in the books with reference to the two Hexagonal minerals, quartz and nepheline. For quartz the ordinary is the lesser index of refraction ; therefore in our phraseology the X-er axis lies across the principal axis of symmetry. For nepheline the extraordinary is the lesser index ; therefore the X-er axis lies along the principal axis of symmetry. Thus quartz is + with respect to its principal axis of symmetry ; and nepheline is −.

OPTIC AXES.—We have already emphasised that the birefringence of a mineral section depends upon the nature of the mineral, the thickness of the section and the direction considered. The direction factor determines that, in any rock slice containing a large number of haphazard sections of some particular mineral cut to uniform thickness, the refractive index of individual sections will range from zero to a definite maximum.

Any isotropic section of a birefringent mineral is said to be at right angles to an optic axis.

Crystals of the Hexagonal and Tetragonal systems have only one optic axis, and are called uniaxial. Obviously this one optic axis must lie along the principal axis of symmetry, and light must be propagated along it with the ordinary refractive index. Such crystals are said to be + if their optic axis is crossed by the X-er axis of the crystal, that is if $\omega < \epsilon$; and vice versa. Thus quartz is a + mineral ; and nepheline is a − mineral.

Crystals of the Monoclinic, Triclinic and Orthorhombic systems have two optic axes, diverging at an angle that is characteristic for the mineral. The two optic axes lie in the *XZ* plane (at right angles to *Y*) and their acute bisectrix is either *X* or *Z*. Biaxial crystals are said to be positive if the acute bisectrix is crossed by the *X* axis ; and vice versa.

As the optic axes are isotropic and at right angles to *Y*, all light is propagated along them with the β index.

UNIAXIAL FIGURE.—A section at right angles to an optic axis is conveniently studied between crossed nicols in convergent light.

A lens, called a condenser, is placed beneath the stage to converge light upon a point in the mineral plate. The high-power object-glass of the microscope is then focussed down to bring the rays, as they diverge after leaving the plate, once more parallel (to observe the result one may either insert an additional object glass, called a Bertrand lens, in the tube of the microscope, or one may remove the eye-piece).

A convergent bundle of rays is rather difficult to think about. It is a great convenience to replace it in imagination by a parallel bundle. Let us take an example.

It is easy to see that a convergent bundle of rays with its axis along the optic axis of a + uniaxial crystal, cut in plate form, produces an exactly similar picture to that due to a parallel bundle of rays traversing at right angles a series of + wedges, radiating from a point (Fig. 67). The argument is as follows :

(1) The ray *AB* is not affected by birefringence, because it is travelling along an optic axis. The ray *A'B'* is not affected by birefringence because it traverses a zero thickness of the wedges.

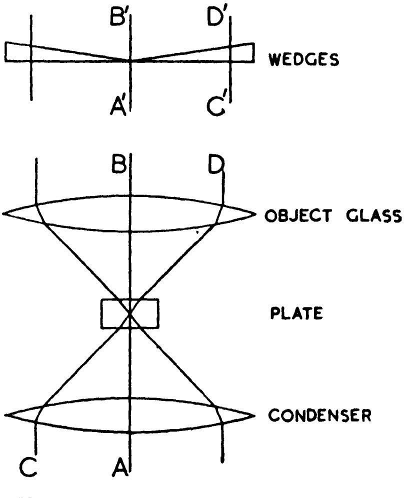

FIG. 67. Diagrammatic comparison of radiating wedges in parallel light and a plate in convergent light.

(2) The ray *CD* suffers birefringence because it is propagated along a direction other than an optic axis ; also the farther *D* is from *B*, the stronger is the birefringence. The ray *C'D'* suffers birefringence because it is propagated through a definite thickness of birefringent material ; also the farther *D'* is from *B'* the greater is this thickness.

(3) Since *AB* is the optic axis of a positive uniaxial mineral, any axis at right angles to *AB* must behave as an *X*-er axis ; therefore in its birefringent course the ray *CD* is controlled by an *X*-er axis perpendicular to the plane

ABD. Since the wedge traversed by *C'D'* is positive, the ray *C'D'* is controlled by an *X*-er axis perpendicular to the plane *A'B'D'*.

Similarly a − uniaxial figure can be imitated by using − wedges.

We can now picture for ourselves the appearance of a uniaxial figure, + or −, due to convergent light directed along the optic axis of a uniaxial crystal cut in plate form (the plate need only be of very small dimensions if accurately centred). In imagination replace the convergent beam by a parallel beam, and the minute plate by a considerably more extensive system of birefringent straight extinguishing wedges.

At the centre of the system there will be black, because the wedges here have no thickness. Black will also extend along the cross-wires, because the wedges give straight extinction (Fig. 68, I). Round the centre, where not obscured by the black arms of the cross, there will be rings of colour, reproducing the succession to which we are accustomed when we look at a quartz-wedge in the 45° position.

If the birefringence of the mineral examined in convergent light is strong, or the thickness of the plate considerable, the colour rings are narrow and crowded. If the birefringence is weak, or the plate thin, the rings are diffuse and widely spaced.

A student with practice and help should be able to get a uniaxial figure from any fairly large isotropic section of quartz in a granite slice. The figure is rather ill defined, owing to the weak birefringence of the mineral.

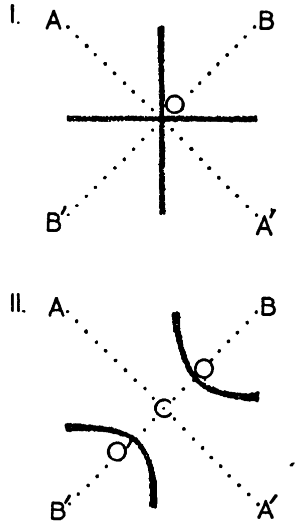

FIG. 68. Diagrammatic comparison of I, a uniaxial figure, and II, a biaxial figure, with the plane of the optic axes in the 45° position. The dotted lines are merely directions explained in the text.

A much brighter and more appealing uniaxial figure is furnished by calcic scapolite—a somewhat uncommon mineral found in certain marbles. A university should have sections of scapolite-marble for beginners in the use of convergent light.

A close approximation to a uniaxial figure is given by any biotite flake placed flat on a glass slip. Biotite is really biaxial, but the divergence of its optic axes is so slight that its figure may be taken as a fairly satisfactory representation of the uniaxial class.

SIGN OF A UNIAXIAL MINERAL.—To determine the sign of a uniaxial figure, treat it as if it were due to wedges radiating from the point *O* (Fig. 68, I) and determine the sign of these imaginary wedges *OA*, *OB*, *OA'*, *OB'*. Any one of our three instruments may be used. If, when inserted along *AA'*, it helps the colours in *AA′*, and hinders the colours in *BB′*, then the figure has the same sign as the testing instrument; and vice versa.

The gypsum-plate is particularly useful for figures with low birefringence. Introduce it along *AA′*. It replaces the black cross by a cross of sensitive violet. If it is helping the hypothetical wedges *OA* and *OA′*, its violet at *O* merges towards *A* and *A′* into blue, and towards *B* and *B′* into yellow; and vice versa. With this simple procedure it is possible to show that the uniaxial figure of quartz is +.

The mica-plate is more useful for figures with moderate birefringence. Introduce it along *AA′*. It replaces the black cross by a cross of grey-white. If it is helping in the *AA′* direction, its white at *O* merges towards *A* and *A′* into yellow, and towards *B* and *B′* into black, and vice versa. Therefore two black dots transverse to the mica-plate mean that the figure has the same sign as the mica-plate; while two black dots along the mica-plate mean that the figure has the opposite sign to that of the mica-plate. With this procedure it is easy to show that scapolite is −; also that the pseudo-uniaxial figure of biotite is −.

The quartz-wedge may be used for figures with close colour banding, where migration of colour is easier to appreciate than change of colour. If on inserting the wedge along *AA′*, the colours migrate in from *A* and *A′* towards *O* (virtually from thick to thin), and out from *O* towards *B* and *B′* (virtually from thin to thick), the quartz-wedge is helping the hypothetical wedges *OA* and *OA′*; and vice versa.

Wherever possible all three instruments should be used. If they give answers that can be interpreted, these answers should agree. With practice proficiency is reached.

BIAXIAL FIGURE.—The biaxial figure, for purposes of utility, may be regarded as a development from the uniaxial figure. The part played by the single optic axis (*O*, Fig. 68, I) of the uniaxial figure is shared by the two optic axes (*O* and *O′*, Fig. 68, II) and the acute bisectrix *C*. The biaxial figure does not remain constant as it is rotated between crossed nicols. When the optic axes lie along a cross-wire there is a black cross centred on *C*, combined with non-circular coloured rings, which, viewed as a whole, are grouped symmetrically about *C*. When the optic axes are rotated into the 45° position, as in Fig. 68, II, the black cross opens up into two separated brushes, while the coloured rings maintain their complicated pattern. The interval *OO′* depends on the optic axial angle (tabulated as $2V$) and greatly helps in the identification of a mineral. For most tests it is sufficient to have one optic axis in the field of the microscope (*N.B.* a student must not risk mistakes by working with a section in which both optic axes lie outside the field). If the optic axial angle is small, the individual brushes will be very curved when examined in the 45° position (Fig. 68, II). If the optic axial angle is large, the brushes become more nearly straight. Whether much or little curved, the brushes in the 45° position always turn their convexities towards the acute bisectrix. In the very special case, where the optic axial angle is 90°, the brushes are straight, and neither bisectrix can be claimed as acute. Accordingly a crystal with $2V = 90°$ does not have an optical sign.

Examples of lowly birefringent high-angled biaxial figures can be easily got by examining isotropic sections of felspars selected from slices of plutonic rocks. Even better for a beginner is the highly-birefringent moderate-angled figure furnished by a flake of muscovite laid flat on a glass slip.

SIGN OF A BIAXIAL FIGURE.—After practice with a uniaxial figure (Fig. 68, I) the sign of a biaxial figure (Fig. 68, II) is easily read. Let us assume that the figure is positive. Then the length AA' in the biaxial figure is +, just as it is in a + uniaxial figure. The only difference is that at the acute bisectrix we find a minimum of birefringence (so far as AA' is concerned), instead of the zero met with at the optic axis O of the uniaxial figure.

Since C is birefringent, and ACA' is +, OCO' is −. It will be noted that OCO' has no analogue in the uniaxial figure.

At O and O' in the biaxial figure there is zero birefringence, just as at O in the uniaxial figure.

OB and $O'B'$ are + in the biaxial figure, just as their analogues are in a + uniaxial figure.

Where only one optic axis is in the field of view, the important point to realise is that BOC changes sign at O. BO within the concavity (obviously equivalent to BO in the uniaxial figure) is +, if the figure is positive; O is isotropic; and OC (without analogue in the uniaxial figure) is −.

The same sort of tests are made as in the case of the uniaxial figure, depending either on change or migration of colour. The student should think out the matter for himself. He has got the gist of it if he realises that insertion of a quartz-wedge, which produces colour migration from B towards O, will at the same time produce colour migration from O towards C, and from C towards A and A'; and vice versa. In fact, so far as colour migration is concerned, the acute bisectrix of a biaxial figure functions as though it were the optic axis of a uniaxial figure.

The value of determining the sign of a biaxial figure is illustrated by the fact that it enables us to distinguish − orthoclase from + albite, and + labradorite from − anorthite. The easily investigated muscovite is −.

PART V

PHYSICAL GEOLOGY

CHAPTER XXX

WEATHERING

UP to this stage attention has been concentrated upon rocks, minerals and maps, because it is possible to handle them in laboratories. Henceforward we shall deal more with the scenic and historical sides of the subject, to which the best introduction comes by way of excursions. Scenery will be treated mainly from the geological standpoint. Land forms will be discussed, and it will be left to the botanical and agricultural good sense of the reader to supply the trees and grass.

Rocks provide the material of landscape. The moraines and drumlins of glaciers, the cones of volcanoes, and the dunes of the shore or the desert furnish instances of scenery that has resulted from accumulation. Still, most scenic features, at any rate in Britain, are a product of sculpture. In the bottoms of river valleys, and over the surface of great plains, there is generally a very characteristic association of accumulation and sculpture.

Rock sculpture is spoken of technically as erosion or denudation. The two terms mean the same thing, namely removal of rock, where rock is used in its broadest sense.

Erosion may take place without preliminary preparation of the material. In much of their activity rivers, glaciers, coastal waves and desert winds attack and destroy fresh rock ; but the way is generally prepared to a greater or less extent by processes grouped under the general title of weathering. Weathering is defined as disintegration or decay produced by the operation of weather.

Weathering agents include frost, change of temperature, wind, rain and underground water derived from rain.

Gravity and organisms often co-operate with and regulate the processes of weathering. Gravity tends to draw disintegrated or semi-fluid or undermined material downhill. Vegetation has more varied tendencies : (1) to supply a tenacious surface that can repair itself ; (2) to regulate the entry of water into soil ; (3) to disintegrate by root penetration and growth, often followed in the case of trees by overturning ; (4) to supply solutions that decompose the rocks chemically. Earth worms, moles, rabbits and other animals bring material from below up to the surface. Overgrazing and ploughing may give opportunity for disastrous soil-erosion by wind or rain.

MECHANICAL WEATHERING.—Where the agents of weathering produce disintegration without chemical change the result is called mechanical weathering. FROST is a very important agent of mechanical weathering. Water swells with enormous force when it freezes. In our homes this phenomenon is fairly commonly experienced in connection with burst pipes during a hard winter. In Nature the process is repeated time after time, so that bedding planes and joints, and even the pores between individual particles or crystals, are wedged open. Thus a rock may be broken by frost into enormous blocks or into a loose grit.

CHANGE OF TEMPERATURE is generally thought to be important in hot arid climates. The sun raises bare rock surfaces to a high temperature to be followed by rapid cooling at night or in the rain of thunder-storms. As the heat comes from the sun the effect is called insolation. Three main effects are attributed to insolation: (1) exfoliation, where a set of joints is produced parallel to the surface of the exposed rock; (2) cracking of pebbles; (3) disintegration, where individual crystals, such as the quartz and felspar of granite, become detached owing to their different coefficients of expansion.

Insolation has recently been questioned by a good observer, partly owing to failure to imitate its effects in the laboratory. Still it seems probable that it is the true cause of many of the effects attributed to it. Rightly or wrongly some travellers say that flints sing at dawn in the Sahara. At any rate, in such regions, a roof of galvanized iron crackles loudly when a cloud passes between it and the sun. Here are two unconnected observations that seem to support insolation:

(1) The rhyolite lavas of Glen Coe every summer lose flakes about the size and thickness of one's thumb nail. It is difficult to understand what but sunshine has detached these flakes.

(2) In the semi-arid wastes of America it is a commonplace to find plateaus covered with ancient alluvial gravels. The hard rounded pebbles are often cracked in half. It is again difficult to explain the cracking except by insolation.

WIND is treated as a weathering agent in so far as it is concerned with the removal of loose particles. When it operates a sand-blast, it is placed in another category. As a weathering agent wind is responsible for the general cleaning up, or deflation, of rock surfaces, which is characteristic of many deserts where accumulation is not in progress. Far-travelled dust-storms are known to all of us, if only by report.

RAIN, before it collects into streams, is regarded as a weathering agent. It washes away loosened particles and softens and weights clay, thus making it flow. The importance of rain depends largely upon its amount, and also upon the humidity or dryness of the atmosphere. The intermittent rains of arid regions may produce marked channelling, and yet leave the solid rock dry.

This favours the opening up of joints and the production of pinnacles (or hoodoos), which in a moist climate would tend to fall through flow of their sodden foundation, a matter that will be considered later in regard to landslips. Here reference may be made more particularly to a curious product of rain erosion known as earth pillars (Fig. 69). Often in a garden after a shower you may notice pebbles standing above the general surface mounted on little pedestals of earth. Each pebble has acted as an umbrella sheltering the earth. Occasionally the same effect is produced on quite a large scale, where rain is eroding a conglomerate or moraine containing large boulders. What are known as earth pillars are produced, each sheltering beneath an umbrella boulder. When this is at last undermined the pillar is washed down until another boulder is exposed. Favourable conditions for the formation of earth pillars are vertical rain and a dry climate, so that the pillars do not get soaked and softened. Good examples are very rare in Britain, but occur at Fochabers in the east of Scotland (conglomerate of Old Red Sandstone).

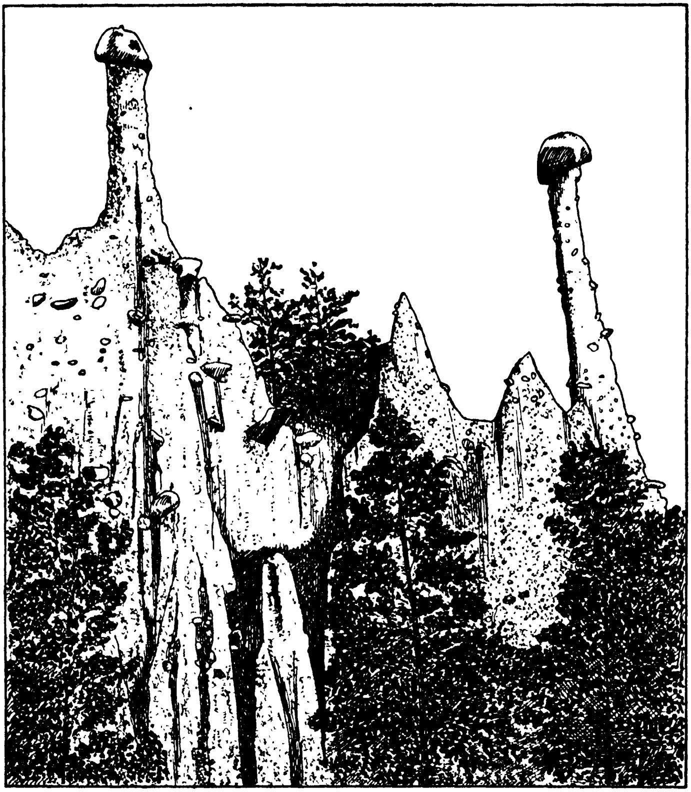

Fig. 69. Earth pillars, Klobenstein, Austria.

Much more impressive developments occur here and there in the Alps (moraine). In one instance it is possible to drive in a large diligence through a tunnel cut in a gigantic earth pillar. Earth pillars are among the most impressive of natural phenomena and highly instructive.

Mention has been made of the effect of vegetation upon weathering. It has been found by experience that forests tend to reduce flooding. One of their main effects is to help the rain to enter the soil, so that its water may take days or months to reach the streams instead of hours. In semi-arid country grass is a great regulator of rain erosion. If the country is overgrazed, the rain strips the surface of its soil.

CHEMICAL WEATHERING.—Attention has already been drawn to chemical processes that affect minerals and rocks during weathering. Here let us briefly sum up the effects. They are mainly due to water derived from rain and charged with a certain amount of CO_2 and O_2. The content of CO_2 is much enriched by passage through soil containing decomposing plant material.

(1) SOLUTION.—$CaCO_3$ may be dissolved, whether it forms the rock limestone or merely acts as cement as in a calcareous sandstone. Gypsum and rock salt are considerably more soluble.

(2) ALTERATION.—Attack upon $CaCO_3$ is emphasized in cities where there is an appreciable amount of SO_2 in the atmosphere. Ordinary weathering may lead to alteration of silicates with production and removal of soluble carbonates ; concurrently Al may be left behind, as hydrated silicate (kaolin) under temperate conditions, or hydrated oxide (bauxite) under tropical conditions. The metals preferentially removed in solution are Ca and Na. The sulphur of sulphides is also leached out after oxidation to sulphate. Fe tends to be retained oxidized and hydrated. In temperate climates the resultant limonite often forms a hard layer known as iron pan at the base of soil below peat. In tropical climates it gives ferruginous laterite, already described.

Here one may refer to a curiosity known as spheroidal weathering, of which there are many examples in Scotland owing to an abundance of susceptible dolerites and basalts. Blocks between joints tend to be attacked by water travelling along these joints and to be weathered into solid spheroids encased in a succession of concentric coats, arranged like the successive coats of an onion. The explanation is that, as dolerite or basalt weathers, it often swells through hydration of its minerals, rather than shrinks through solution, and each swollen superficial layer detaches itself from the sound core. Some authors give another explanation, and believe that spheroidal weathering is guided by spheroidal cooling cracks. This does not seem to be the case, because sediments rich in igneous debris fairly often show spheroidal weathering (Fig. 70). Spheroidal weathering is also well developed in a glauconitic greensand south of New York.

WEATHER ACCUMULATIONS.—Certain accumulations in which there has been comparatively little transport may be treated as direct products of weathering. They have been to some extent already considered under the head residual deposits (Chapter VI). Their nature varies according to many factors, such as original rock, exposure and climate.

Boulder fields are characteristic of many mountain tops like that of Ben Nevis. Frost has been very important in opening joints and breaking surfaces. Vegetation is lacking, and the wind blows away all fine material. The power of the wind is very obvious on some of our Highland tops, where, for instance, a knob of white vein-quartz, surrounded by dark schist, may have served as source for an extensive trail of fragments.

Fig. 70. Spheroidal weathering in grit, Inishowen, Donegal.

Talus, or scree, is a related deposit, forming an apron spread over slopes beneath rock exposures. Frost again is of prime importance. To develop a great scree, the rate of production of the scree must counterbalance the rate of wastage. Screes are particularly big in arctic countries. They are small or absent in deserts, where the fallen material is supplied so slowly that it often disappears as dust without making an appreciable accumulation. Screes are also at a minimum on live sea and river cliffs, where removal at the base is, of course, particularly active. In an ordinary scree the fragments are weathered from all sides, and may be soaked with percolating waters that emerge at the base in springs. All this tends to keep them in check. Much of the movement of the material of scree is due to fall and jump and roll, and the passage of animals. Much is of a slow recurrent nature spoken of as surface creep.

In surface creep the superficial material of a slope, including even the upper part of the solid rock, tends slowly downhill. This is due to recurrent disturbance through alternate wetting and drying, freezing and thawing. If the material swells by wetting or freezing it will swell downhill rather than uphill ; and when it contracts again on drying or thawing it will contract downhill, rather than uphill. Surface creep, or solifluxion as it is often called, has to be guarded against where roads and railways cross steep hill slopes. The road may be dug down to a firm foundation and embankments, or revetments, built above it, also on firm foundation, to hold the creep in check. In the Alps, and even at home, the solid rocks may be so pulled out of position by surface creep that dips observed at the surface may be quite untrustworthy. The term surface creep is sometimes applied to the material that has crept, as well as to the process of creeping.

Solifluxion is not altogether confined to slopes. If a flat superficial deposit contains internal water and is subjected to freezing, the disseminated ice swells upwards, thus tending to tilt towards the vertical any associated elongated pebbles that happen to start in an inclined position. On thawing the contraction of the water allows of a readjustment of the deposit as a whole, and it is unlikely that the pebbles will regain their original attitude. Thus frequent repetition of freezing and thawing produces a cumulative effect. Many gravels of the South of England were long exposed to tundra conditions during the Glacial Period, and record the fact in an upper zone, some few feet thick, in which the pebbles are characteristically up-ended. A more spectacular, though less easily explained, result of solifluxion is known in many subarctic lands under the name of stone polygons. In these the stones of a clay-with-stones deposit have been segregated into vertical fissures with polygonal plan. The fissures presumably have resulted from contraction, due possibly to excessive freezing or to thaw, and have served as efficient traps for any stones that have been washed over the surface.

RAIN WASH is another term which, like surface creep, may mean either a material or a process. In the former sense it is fine material washed along by rain water that has not collected into definite streams. A combination of surface creep and rain wash produces a series of parallel scarps and terraces on many of our exposed Highland tops. The scarps slowly advance, upturning sods and heather. Their progress is not directly downhill, for it is very distinctly influenced by the direction of the prevalent wind.

LANDSLIPS, or LANDSLIDES, are on a bigger scale again. They may be of solid rock, measuring miles in horizontal extent, or they may be of debris. They may go at a disastrous pace and cause catastrophe, or they may go slowly and merge with surface creep.

Landslips generally take place after rain, or thaw, or earthquake, or undercutting by stream or sea.

They are particularly liable to occur where bedding, or less often joints, dips downhill at a gentler angle than the slope of the hill, especially where permeable material such as chalk rests upon a clay. Throughout much of the South of England, the Chalk is underlain by a clay known to geologists as the Gault, but to others not infrequently as the blue slipper. The chalk on wetting becomes additionally heavy, and the clay below becomes lubricated.

Miners thoroughly understand the common-sense relationship between landslips and dip, and, if possible, they pile their bings of waste material on the down-dip side of their shafts.

Landslips, however, often occur on steep slopes without any obvious structure to help them. The following features are very characteristic :

(1) A semicircular cliff from which the landslip has detached itself.

(2) A broken uneven surface marked by pools and fissures.

(3) Two banks built up of material stranded at the side during the general downhill rush.

(4) Springs issuing from the end.

In mountainous countries landslips may cause damage, either by direct overwhelming of villages, etc., or by damming temporary lakes, which later may produce disastrous floods by digging rapidly through the incoherent obstruction.

Vertical fissures are a general early feature of land-slipping. Where danger is apprehended the growth of such fissures may be kept under observation for years.

The grandest landslips of Britain are those of northern Skye, where Tertiary lavas intermittently slide over Mesozoic sediments, giving rise to magnificent unexpected precipices, pinnacles and hollows. In England, the undercliff of the Isle of Wight furnishes another noteworthy example. Here Upper Greensand of the Cretaceous System moves forward over Gault Clay ; and the Greensand scar, from which the last addition to the landslip originated, dominates a vast irregular tumbled slope leading down to the seashore far below.

Landslipping and surface creep are among the most potent methods of erosion in a climate such as ours. In arid countries they do not ordinarily occur. Great cliffs of clay stand firm, that here would resolve themselves into confused slopes of sludge. It is only in such countries as Egypt and Iraq that sun-dried bricks are of much use.

AVALANCHES are a particular type of landslip, where snow furnishes most of the material. They are responsible for a great deal of erosion in high mountains.

SOIL is the most important accumulation due to weathering. It is fine-grained mineral matter containing a certain amount of plant and animal material and capable of supporting plant life.

Soils are being very closely studied at the present time, and are classed under two main headings :

Sedentary soil is derived from solid rock. The intermediate zone of partly broken up and decomposed rock is called subsoil.

Transported soil is derived from material, such as river alluvium or glacial drift, which forms a cover of recently transported material on top of solid rock.

This classification is unfortunate in that it deals with the substratum rather than the soil itself. Soils are apt to receive much of their material from above, as dust, clay, sand, etc., blown or washed over the growing plants. It seems a pity that transported soil does not mean a soil largely formed by contemporaneous transport.

Many soils consist of material that has been left after other material has been removed in solution (leached out). These residual soils have been dealt with in Chapter VI. They include the bauxitic and limonitic laterites of the tropics.

WEATHER SCULPTURE.—A large proportion of the sculpture of landscape is directly due to weathering. The following are characteristic examples :

(1) OPENING UP OF VALLEYS.—Rivers cut narrow gorges or canyons ; the opening up of such gorges into V-shaped valleys is due to surface creep and landslip (Fig. 71). The river at the bottom removes the material supplied by weathering in addition to the material which it itself erodes. As already pointed out, surface creep and landslip are reduced to a minimum in arid regions. It is on this account that canyons are so common in arid regions.

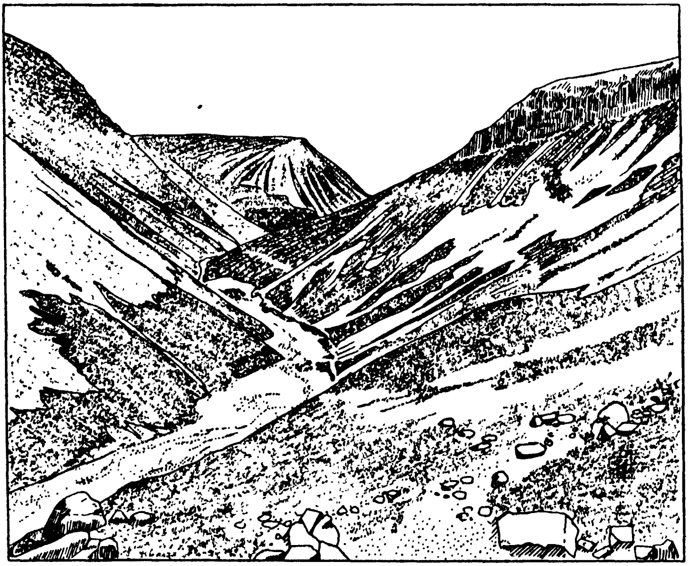

FIG. 71. V-shaped valley, Glen Feshie, Kingussie. (Geol. Surv. photo.)

(2) Differential weathering along beds gives rise to escarpments and dip slopes or terraces. The soft material wastes away and undermines the hard material, which breaks off along its joints leaving a steep cliff. The production of scree tends to check this differential weathering, by draping the whole surface with a uniform cover derived from the debris of the harder rocks. In arid or semi-arid regions, where little or no scree accumulates, the detail of scarp and terrace is amazing in its perfection (Fig. 72). In our own country a succession of lavas very often shows scarp and terrace featuring. The top of a lava flow is commonly full of vesicles, and its easy weathering may thus undermine the non-vesicular portion of an overlying flow. The result is a sort of natural staircase ; and lavas on this account have been called trap rocks, where *trap* is the Swedish word meaning step.

Fig. 72. Erosion of resistant and non-resistant formations under semi-arid conditions. Looking N.E. over the Finke Gorge, Central Australia. (R. Aust. A.F. photo.)

(3) Differential weathering along joints may lead to the production of chasms. This result is especially pronounced in hard limestones, where the joints guide solution. It is also very marked in desert regions, where nothing accumulates to mask the structures in the rocks, so that joints, like bedding, can be employed to full advantage. By enlargement of joints the intervening rock may be left standing as pinnacles (hoodoos).

(4) Residual boulders.—Where certain parts of a rock are specially resistant, they may be left as groups of residual boulders, sometimes of immense size. The granite tors of Devon furnish familiar examples. Scotland probably had many tors before the Ice Age, but most of them have been swept away by glaciers.

The Chalk districts of Salisbury Plain and other parts of the South of England afford another very interesting type of residual boulder. The Chalk of these parts was formerly covered by Eocene sands, parts of which were compacted into quartzite concretions of large size. The unconsolidated sand has been washed away leaving huge residual boulders of quartzite known as grey wethers from their resemblance in the landscape to scattered sheep. From time immemorial the grey wethers have been quarried for building stone—they furnish the outer ring of Stonehenge—so that comparatively few can now be seen in a natural setting.

CHAPTER XXXI

UNDERGROUND WATER

WATER TABLE.—It is now convenient to consider drainage problems. The rain that reaches the surface is disposed of by :

Evaporation.
Surface run-off into streams.
Percolation.

The term run-off is used in two different senses :

(1) The surface or direct run-off of an area is that part of the rain water, which, falling within the area, reaches streams without intermediate percolation.

(2) The total run-off is all the water discharged from the area by streams. Obviously even a rainless area may have a run-off in this sense.

Let us pass on to the typical distribution of underground water as depicted in Fig. 73.

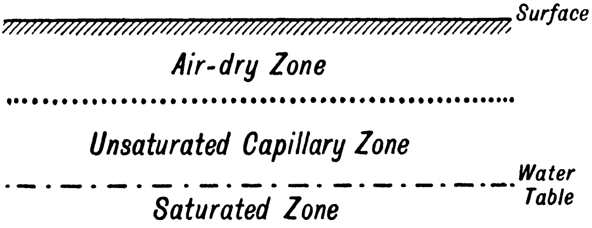

FIG. 73. Underground distribution of water.

The distribution may be, and often is, much more complicated. Thus :

(1) During or after rain an unstable saturated zone, with gravity-streams descending from its base, may be superimposed upon an unsaturated, even an air-dry, zone.

(2) Owing to the presence of impermeable layers of rock (Chapter XI) there may be a series of independent zones following one another in depth. Thus a bore may reach water in a saturated sandstone at 100 feet, and lose it after passing through a shale and meeting air-dry sandstone at 200 feet. This relation affords an example of what is known as a perched Water Table.

Let us return to the simple case and start at the bottom.

In the Saturated Zone all open spaces are filled with water. The upper limit of this zone is called the Water Table. The saturated zone is only effective for a few thousand feet below the surface. Beyond this, pressure closes all but very minute openings.

In the Capillary Zone water is held (as in blotting paper) by capillarity (surface tension) in the natural tubes of the rock or soil. The finer the bore of the tube, the higher is water held above the water table. *Capilla* is a Latin word meaning hair. A tube with a hair-like bore raises water very appreciably. Towards the bottom of the Capillary Zone most of the tubes are full; towards the top only the finer ones are full.

In the Air-Dry Zone there is a certain amount of moisture condensed on the surface of soil particles depending on the dryness of the air, and that is all.

Most plant roots must have both air and water. They do not grow below the water table. This explains the advantage of draining clay soil. In ordinary clay soil in our country the water table remains for much of the year near the surface. This restricts root growth to the top layer, which is completely dried out in drought. Drainage, by helping the slight permeability of the clay, takes down the water table in normal weather some few feet below surface. This allows of deep rooting, in a layer that is thick enough to escape complete drying during drought.

Spring rolling is to compact the topmost layer and thus increase capillarity, so as to bring water up to the roots of seedlings.

Summer hoeing is to break up the capillary tubes near the surface and thus check evaporation. The roots, now deep, find water lower down.

SPRINGS.—If we enumerate a few simple circumstances that affect springs, it may help us to understand natural occurrences of more complex character.

(1) Where a hill of permeable material receives rain, it may become saturated through and through. In this case the water table corresponds, for the time being, with the surface of the hill; and the water tends to escape as springs at any point below the summit. As the hill dries, the water table descends to a position roughly corresponding with the season. It keeps an arched shape, conforming more or less with the surface of the hill, but it only meets that surface at comparatively low levels. Anywhere below the intersection of surface and water table, springs may occur (Fig. 74). Obviously, permanent springs are not to be found at the tops of our Highland hills, a matter that may determine the luncheon site of a party climbing a mountain like Ben Nevis.

FIG. 74. Position of water table (dot and dash) in a hilly country made of permeable material.

(2) Where a barrier prevents permeable material, that is exposed on upper slopes, from outcropping on lower slopes, it fixes a local lower limit to springs that can be fed from the permeable formation. The barrier may be of any impermeable material such as shale, basalt or boulder clay. It may have any inclination, from horizontal to vertical, so long as it excludes its permeable associate from access to the lower slopes. Representative possibilities are illustrated in Figs. 75 *b-f*.

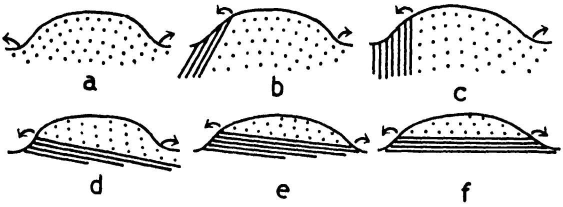

Fig. 75. Effect of a barrier of impermeable material (lined) in locating the lowest level of springs (arrows) from permeable material (dotted).

(3) If, as in Fig. *e* and *f*, the permeable material occurs as outliers completely underlain by impermeable material, local springs will depend entirely upon local conditions of rainfall, evaporation, topography and structure.

(4) If, as in Fig. 75 *a-d*, the permeable material continues underground for some distance, the way is left open for loss, or gain, of water through underground drainage.

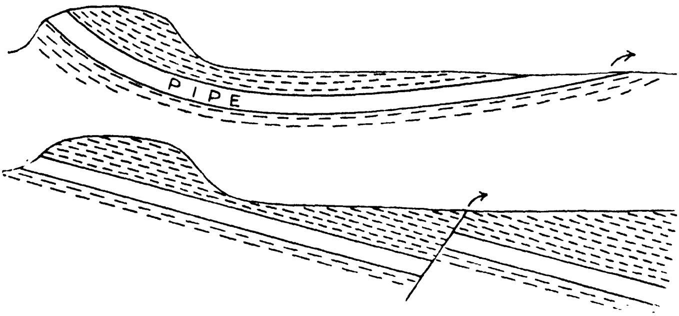

Fig. 76. Pipe-like layer of permeable material (unornamented) interbedded between impermeable (ornamented) and locating distant springs (arrows), either directly or through a fault.

(5) Let us consider the non-local aspect of springs a little more closely. If permeable material is overlain and underlain by impermeable material it acts like a pipe (Fig. 76). If this virtual pipe is inclined, it tends to supply far-travelled water to springs at its lower outcrop.

(6) If the pipe, before reaching a lower outcrop, is broken by a fault then it is likely to leak and establish springs along the course of the fault, at any place where the fault happens to outcrop on ground that is lower than the intake of the pipe. This is because faults, with their belts of shattering, are usually permeable to water. The resultant springs are of artesian type (Chapter XI).

The permeation of water through permeable material is often largely or wholly confined to joints. At Dumbarton Rock, for instance, numerous little springs issue from the joints of an otherwise impervious basalt.

Spring water is apt to be hard through having dissolved salts of Ca, Mg or Fe on its underground journey.

Brewing water must be free from Fe, and yet Edinburgh and Burton both use water derived, by boring, from ferruginous sandstone. This apparent contradiction is readily understood for the limonite cement of a red sandstone is insoluble.

Springs that carry an unusual proportion of mineral matter in solution are called MINERAL SPRINGS. The nature of the material varies. Thus chalybeate, or iron-bearing springs, and sulphur, or H_2S-bearing springs, occur at Strathpeffer and Harrogate ; and magnesian, or $MgSO_4$-bearing, springs occur at Epsom. The chalybeate and sulphur springs may derive their contents from the underground decomposition of iron sulphide. It is difficult to suggest an origin for Epsom Salts.

HOT SPRINGS are rare in Britain, but are found at Buxton and Bath. Any one visiting Bath should be sure to drop in to the Roman Baths. The hot water at these two localities must take an unusually deep course. In volcanic regions, such as the Yellowstone Park, high temperatures are soon encountered underground, and hot springs abound. Most of their water comes from rain, as is shown by seasonal fluctuations ; but some is magmatic, as is indicated by accompanying gases.

CIRCULATION THROUGH LIMESTONE.—Percolating underground water, even at ordinary temperatures, may produce great effects in washing out lighter substances such as gas and oil, and in removing soluble substances such as salt, gypsum or calcium carbonate, or, on occasion, in precipitating cements. Let us now consider some of the solution phenomena found in limestone country.

If the limestone is soft and porous like chalk,* the attacks of weather under present-day British conditions give rounded, dry, but grass-covered hills—the chalk downs. Clay with flints is left as a widespread residual deposit. Percolation along joints causes holes with superficial subsidence, called pipes or sinks. Thus pipes, filled with clay with flints, are very

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* For water supply purposes the permeability of the chalk depends mainly upon jointing and upon solution channels supported by adjacent flints ; but the porosity of the formation probably influences its weathering.

commonly seen at the top of chalk quarries or railway cuttings. Underground drainage is diffuse, and does not give rise to caves. The chalk downs have many beautiful river valleys, few of which are occupied by rivers. Some of these dry valleys have probably been eroded when the chalk was frozen impermeable under glacial conditions.

Where the limestone is hard, permeation is limited to joints, which are opened by solution down to the lower limits of circulation. Streams pass below ground, and the surface is left bare, barren and craggy, with numerous sinks, swallow holes and caves. This type of country is called karst land, after a typical representative on the shores of the Adriatic.

The underground drainage becomes saturated with $CaCO_3 . H_2CO_3$, and, wherever through ventilation it loses water or CO_2, it deposits stalagmites, stalactites, tufa (travertine) or calcareous cement, according to position.

The tracing of underground water may become an important matter because :

(1) There is no filtering of an underground river to prevent pollution of drinking water. A well-known geologist was once staying at a hotel in Yorkshire. He experimented and found that water took only 45 minutes to travel from drains to well. He didn't take as long in changing quarters.

(2) In the Alps, where rivers of the limestone country are often impounded for power, it is necessary to know in advance whose water supply is to be affected. Supposing the river a little below the site of the dam has been accustomed to plunge down a swallow hole, it may have reappeared at any lower level, even across a watershed.

The exit of underground streams can be traced by using a fluorescent dye called fluorescein. This substance, dissolved in strong potash, gives an orange solution, but on dilution, even with an extremely large proportion of water, it develops a beautiful green fluorescence. A pound of fluorescein solution is put down the swallow hole, and for the next few days a watch is kept upon suspected springs. Fluorescein does not harm fish or man.

Karst land is rare in Scotland, where there is only one very important limestone. This is the Durness Limestone with an outcrop reaching from Durness to Skye. It gives all the typical phenomena. In England the widespread Carboniferous Limestone furnishes most of the inland caves of our islands.

CHAPTER XXXII

RIVERS

RIVERS are responsible directly or indirectly for most erosion.

They derive their water from :

(1) Surface or direct run-off.
(2) Snow and glaciers.
(3) Springs.

The two first are responsible for floods. Our floods, due to rain, come mainly in the winter. Alpine floods, due to melting snow and ice, come mainly in the summer.

River erosion may be considered under two headings :

(1) Corrasion or mechanical erosion.
(2) Corrosion or chemical erosion.

Except where corrosion is very important, rivers flow above ground.

Models of corrasion are familiar to all of you on the seashore, laid bare by a retreating tide. Rivulets dig miniature valleys for themselves and assemble tributaries. Deeper-cut models are afforded by the waste heaps of mines, by the dissected ash cones of volcanoes, and by the bad lands of semiarid regions (Fig. 88).

Rivers carry a load which may be classified as follows :

(1) Material in solution.
(2) Material in suspension.
(3) Rolled material used as tools.

A river has very little power to corrade consolidated rocks until it has furnished itself with tools.

The transporting power of a current increases rapidly with velocity. A simple approximate calculation shows that it is proportional to V^6, by which is meant that if the velocity of a stream is doubled it can move pebbles $2^6 = 64$ times as heavy as before. Streams in flood have both bigger volume and bigger velocity than in normal times ; it follows that streams do most of their transport and erosion under flood conditions.

Streams can corrade downwards so long as their transporting power is not fully employed. They can still corrade laterally when fully loaded, for they can pick up a new load at one point and drop an equivalent close at hand. A stream is often eroding on one bank while depositing on the other.

Vertical corrasion acting alone produces a canyon or gorge. Weathering, as already noted, tends to produce scree, surface creep and landslip, and thus to open canyons into V-shaped valleys.

Canyons therefore only occur where corrasion has outstripped weathering. Favourable conditions are :

(1) Rapid corrasion ; example, the gorge of Niagara (Fig. 77).

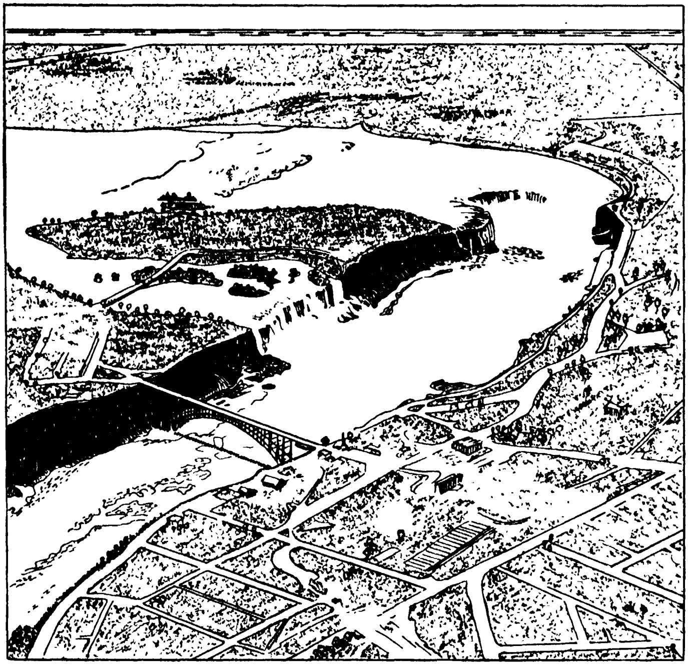


FIG. 77. Niagara Falls.

The American Fall, near the International Bridge (since destroyed by ice) and the Canadian, or Horseshoe, Fall as seen from a height of 2000 feet. Goat Island separates the two falls. (Airmap Corporation photo.)

(2) Local material resistant to weathering ; example, Finnich Glen near Glasgow, where a perfect canyon has been cut in a good building stone, the Old Red Sandstone.

(3) Weathering reduced by aridity ; example, the canyon system associated with the Grand Canyon of the Colorado in Arizona. There is so little surface water available on the plateau cut by the Grand Canyon that the Grand Canyon hotel has to pump its drinking water up by petrol pump from a spring far down the canyon side.

It is obvious that any cause which hinders the opening up of a valley assists the stream in its work of downward corrasion. Conversely, a full load of material supplied from its sides will prevent any stream from digging downwards.

Corrasion acts by :

(1) GRINDING.—This leads to a moulded channel. In particular, where pebbles are imprisoned in hollows, and whirled round by currents, they may dig out great rounded holes, known as potholes (Fig. 78). Moulding, including potholes, is characteristic of fairly soft, but tenaceous, material, like slate, limestone, sandstone.

FIG. 78. Pothole, Glenariff, Antrim. (J. R. Welch photo.)

(2) QUARRYING.—Boulders and small fragments are detached along planes of weakness furnished by joints and bedding. The resultant river bed is fairly angular. Examples are afforded by quartzite and granite.

(3) UNDERMINING.—If a hard rock is underlain by a soft rock, the removal of the foundation leaves the hard rock unsupported so that it breaks away along joints. The falls of Niagara, and most other waterfalls in the world, are produced in this way. At Niagara hard limestone is underlain by soft shale. In the Campsie Fells there are many miniature Niagaras. The Spout of Ballagan, for instance, falls over a sandstone overlying shale. Many other falls of the same district fall over the hard lower portion of a lava flow resting on the soft weathered slaggy top of another lava flow.

Though most falls result from the undermining of hard rock resting on soft, some follow from other conjunctions of hard and soft rocks. For instance, in Campsie Glen there is a waterfall over a dyke that cuts through shales. The shales on the downstream side have been rapidly cleared away leaving the dyke standing as a retaining wall that shelters the upstream shales from attack. The same principle is illustrated on a much larger scale in the famous Yellowstone Canyon. The canyon has been cut in rhyolite lavas softened by the previous attack of hot springs. At two places, however, the springs have developed vertical belts of compact silicification, thus hardening instead of softening the rock. At these two places we find magnificent waterfalls.

Soft vertical belts in hard rocks also may produce falls. Often in the Highlands we find a stream tumbling into a gorge which has been excavated along a vertical shatter-belt. The most magnificent example of this type of fall is afforded by the Victoria Falls of the Zambezi. The river at present hurls itself headlong into a narrow gorge, which does not lead straight away from the fall, as at Niagara, but follows a series of amazing zigzags. At one time people thought that these zigzags could not have been produced by erosion, but the evidence is conclusive :

(1) The zigzags are confined to the old broad high-level bed of the Zambezi. If they were earthquake rents this would be unintelligible. If, on the other hand, they follow intersecting crush-zones extending far beyond the river bed, but only eroded into gorges as opportunity afforded, it is just what one would expect.

(2) The downstream portion of the Zambezi gorge is V-shaped. The portion near the falls is a canyon. Evidently the downstream portion was formed long before the portion that neighbours the present fall. This shows that the gorge is not a fissure produced instantaneously by an earthquake, but a gorge opened progressively by erosion upstream from the margin of the tableland.

Measurements have been made of the rate of river erosion. The Horseshoe Fall at Niagara is going back at the rapid pace of 5 feet horizontally per year. This sort of pace is, of course, very exceptional. The Mississippi, which is often considered an average river, is removing 1 foot vertically per 5,000 years. This may seem slow, but a goods train, long enough to carry one year's load for the rivers of the U.S.A. would reach six times round the world. Some train!

Material deposited by rivers is called alluvium. It may consist of gravel, sand, loam, or clay. It may be deposited on river bed, on temporarily flooded land, or in lake or sea.

Where a river loses transporting power it drops some of its load. If the river is not confined within a valley, the deposit tends to spread out laterally downstream giving a fan-shaped deposit called a delta.

Such loss of transporting power follows from :

(1) Change of slope, often affecting a mountain torrent.

(2) Evaporation, typical of temporary rivers of deserts.

(3) Entry into standing water.

Causes (1) and (2) lead to dry deltas or cones of dejection.

Deltas often furnish a vivid proof that valleys are due to erosion, since in them one sees much of the eroded material.

Where a river drops material in its bed it tends to build it up, which helps to change the position of the river bed, and also to produce temporary flooding. Flood water outside a river channel is shallow and therefore relatively slow. It readily drops its load, especially if it is strained through vegetation. Thus alluvium is intermittently added to flood plains. Growth is most rapid along the edge of the river, since the flood water here drops its coarser portion. This leads to the production of natural embankments, or *levées*, which may be raised and strengthened by man. The bursting of such embankments is an added element of danger in exceptional floods.

A river that is building up its bed with deposit is said to be aggrading.

An eroding river is said to be degrading.

A balanced river, which on the whole is neither depositing nor eroding, is said to be graded.

The balance between deposit and erosion is easily upset, for instance by change in climate, or change in elevation, or many other causes. Thus alluvium often occurs in a river valley in the form of partially eroded terraces. The higher terraces are earlier than the lower terraces. In high terraces of the Thames, Palaeolithic weapons and bones of mammoth are often found. In the alluvium that is collecting to-day bits of motor cars are characteristic fossils.

Sea-level is often called the base level of stream erosion, although rivers do cut a little below sea-level; for instance, the Mississippi cuts down 100 feet below sea-level.

Local or temporary base levels of erosion are afforded by lakes or outcrops of particularly hard rocks; also, so far as its tributaries are concerned, by a main river, where the latter has attained a relatively stable condition. The tendency of river erosion, helped by weathering, is to reduce all the world to sea-level; and meantime to reduce individual areas to their local base levels. As base level is approached erosion becomes very slow, and so the word peneplain has been introduced to denote a stretch of country that has been almost planed down by erosion.

The summits of the Scottish Highlands belong to a much dissected peneplain standing 3,000 feet above sea-level. Most of Canada is a peneplain.

Thalweg is another term that you must understand. It means in German the *weg*, or way, of a *thal*, or dale. Its scientific definition is the actual course of a river straightened out into one vertical plane so as to show the relation of height (measured above some datum such as sea-level) to length (measured along the bed of the river).

As a river in a humid climate generally increases in volume with length, measured from the source, and as erosive power is greatly helped by volume, there is a tendency for the lower part of a thalweg to approach the base level of erosion more rapidly than the upper part. Accordingly a very typical form of thalweg is a curve that is concave upwards until at sea-level it becomes horizontal.

We may now pass on to certain other general characteristics of rivers.

Rapidly eroding streams gather tributaries.

Rapidly depositing streams, where bottom load is deposited, supply distributaries. Distributaries on a delta often find independent courses to the sea. Distributaries within a valley or on an inland plain often reunite and give rise to braided streams. The formation of distributaries constitutes one of two main methods of river wandering. A distributary may easily transform itself into the main river.

Where a river is neither rapidly eroding nor rapidly depositing, that is where it has approached the neutral graded condition, meanders, or looped bends, are frequently developed by lateral corrasion (Fig. 79). This is the second main method of river wandering, through modification of the old bed rather than exchange. It is favoured by vegetation, which tends to stabilise alluvial forms through providing a temporary organic cement of roots and rootlets.

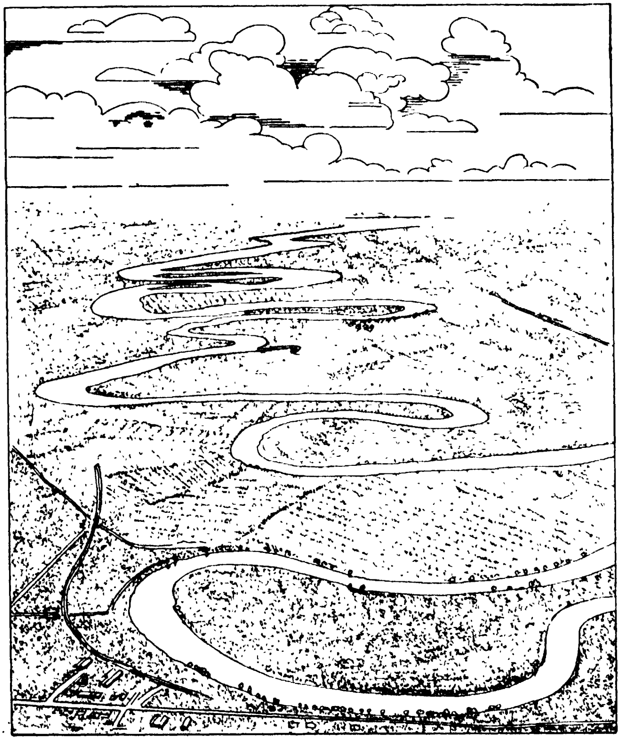


Fig. 79. River Forth meandering from Stirling to the sea.
(A. G. Buckham photo.)

The initiation of meanders is easy to understand, for if any accident carries the main current against one bank it will dig into that bank and then rebound downstream against the other. Erosion due to diversion of this sort tends to make a river bed bend, but not broaden. If the main current is attacking one bank, then slack water will lead to compensating deposit just opposite along the other bank.

Rivers fit their meanders; large rivers have large meanders, and small streams have small meanders.

This adjustment is due to two opposing tendencies:

(1) Weight tends to draw the main current along the inner bank, because this is the shorter route.

(2) Momentum tends to carry the main current against the outer bank, although this means a longer journey.

Where a river fits its meander these two tendencies keep the main current midstream. With decreasing flow, the momentum factor is reduced in relative importance and the current attacks the inner bank, and so contracts the meander until equilibrium is re-established. Conversely, with increasing flow, momentum leads to attack of the outer bank, and the meander expands. In either case alluvium is added to the slack-water bank.

Here are a few additional points about meanders:

(1) They lengthen a river and thus flatten the thalweg.

(2) Often during the development of meanders there is concomitant vertical corrasion. This leads to development of cliffs along outer banks and gentle slopes along inner banks.

(3) Meanders often short-circuit by cutting into one another. This sometimes leaves crescentic lakes known as deserted oxbows.

(4) Meanders are also often short-circuited during floods, when overflow cuts the isthmus.

Short-circuiting a meander reduces the total length of a river. Mark Twain was so much impressed by the hundreds of miles lost by the Mississippi during a disastrous flood, that he calculated how long it would take for the whole river to disappear. Though it has nothing to do with the subject, it is interesting to remember that Mark Twain's *nom de plume* was taken from the Mississippi pilots' call registering a safe two fathoms of water as revealed by sounding.

Wandering rivers, whether the wandering is determined by distributaries or by meanders, are potent agents for broadening valleys and developing peneplains. A river does not lose its power of lateral corrasion when fully loaded, because, as I have already pointed out, it can pick up material on one side of its course and drop it on the other. In our own country we are accustomed to see almost flat river alluvium in valley bottoms. Where this alluvium consists of gravel it must have been directly deposited by the river current during wanderings. It is very common to find a gravel deposit lying as a thin coating upon an almost flat surface of eroded rock. The river which deposited the gravel has also, during its wanderings, cut the valley bottom to one approximate level. If the river during its wanderings has been intermittently cutting downwards, as well as sideways, then it will have developed a series of terraces of erosion, each capped with gravel—a very common phenomenon. All this has been thoroughly understood for a long time ; and it has been realised that rivers, when they have ceased to cut down their valleys actively, may still broaden them very considerably.

Recently American geologists have been studying their semi-arid districts with increasing thoroughness. It has already been pointed out that the downward cutting of a river running through a desert is particularly clear, because the sides of a canyon have so little tendency to fall. In other situations, where desert rivers are graded and have no tendency to dig themselves in, their lateral corrasion is equally easy to recognise. Concomitant weathering is so slow that, as the rivers wander to and fro to make immense plains, their workmanship is left unblurred. The plains are covered by river gravel, if the rivers are transporting hard material as pebbles ; and the different plain levels are separated by river scarps, such as separate the comparatively miniature terraces of our own valley bottoms.

CHAPTER XXXIII

RIVER DEVELOPMENT

RIVERS show certain natural stages of development and these have been well called youthful, mature and senile. Their characters may be summarized as follows :

YOUTHFUL.—Canyon valleys. Rapids or falls. Vertical corrasion predominant. Much of the country between neighbouring rivers scarcely affected. Discordant or hanging tributaries.

MATURE.—V-shaped valleys with bottoms broadening by lateral corrasion into meander belts. Gentle approximately-graded thalwegs. Transport of mechanical detritus supplied by surrounding country predominant. This surrounding country fashioned into valleys with narrow divides. Tributaries concordant. Adjustment of river courses to geological structure so arranged that most of the flow takes place along the less resistant outcrops.

SENILE.—Valley systems so open and flat as to merge into a peneplain, much wider than any individual meander belt. Lateral corrasion and chemical erosion predominant. Loss of adjustment to the nature of the rock outcrops.

The disappearance of waterfalls with advancing age is interesting. Let us take the common case of a waterfall over horizontal hard rock on to soft (Fig. 80). The waterfall will retreat upstream by undermining only so long as the stream below the fall has sufficient gradient to transport the eroded material. Once the stream below the fall is graded it will tend to be blocked by debris, which, by forming a barricade, with or without a pool, will check undermining at the foot of the fall. Suppose A is some point at local base-level, and that, upstream from A, there is a waterfall at B. The waterfall can retreat upstream, if AB is not graded, until some point C is reached, where AC is graded. Thereafter the base of the fall, no longer undermined, remains at C, and the cliff of the fall is gradually worn down, so that the fall degenerates to a rapid of lessening slope. That the retreat of a waterfall depends largely upon its ability to keep its base clear is well illustrated at

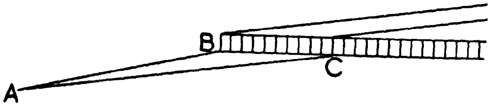


FIG. 80. Retreat of waterfall from B to C, until AC is graded.

Niagara. The Canadian, or Horseshoe, Fall has so much water that it can prevent accumulation of debris, and it retreats 5 feet a year. The American Fall, with less water, tumbles over the side of the gorge cut by the Canadian Fall. It cannot move the great blocks that fall from its crest, so that relatively speaking it stands still (Fig. 77).

The complete development of a river system, from the beginning antedating youthful to the end of senile, is called a cycle of erosion. The name is intended to suggest the similarity of the featureless start and featureless conclusion. Often some cause, such as earth movement, quickens erosion at some stage in the cycle. Rivers which have their activity renewed are said to be rejuvenated. A rejuvenated river system has many features of a youthful system such as canyons, falls, rapids, discordant tributaries ; but it also may inherit features from its previous mature or senile condition. Thus the Zambezi gorge has been sunk into a still recognisable senile bed ; or a meandering river rejuvenated may have dug down its meanders giving rise to what are called incised meanders.

The topography of a river system is as old as it looks : it does not depend merely upon years, but partly also upon substance. Hard resistant rocks retain youthful topography long after soft unresistant rocks have adopted mature or senile form. Thus along the course of a single river one may find reaches, traversing hard rocks, with falls and rapids confined in gorges, and other reaches, traversing soft rocks, with sluggish meanders on alluvium spread over a peneplain.

Hard and soft rocks often lead to a profound readjustment of river courses within a wide area. Rivers unite into systems so as to reduce their crossings of hard resistant outcrops to as few as possible. This is a very common feature of maturity in river development.

The first chapter in river development is the establishment of river valleys as a direct consequence of uplift. The streams are called consequent streams. To begin with they flow down dip slopes ; but after a time with the help of weathering they tend to cut down the country as a whole to a gentler inclination than the dip of the strata. The recognition of consequent streams in a maturely adjusted river system is often speculative, but the Humber, leading from the Pennine uplift, and the Medway and Arun radiating north and south from the Weald dome may be taken as safe examples.

It is good practice to draw an ideally simple map of a series of parallel consequent streams traversing at right angles a succession of hard and soft outcrops with seaward dip (Fig. 81, 1).

The second chapter in the development of a river system is the establishment of tributaries. As the consequent rivers dig in they develop slopes leading to themselves from either side. The hard rocks, resistant to weather, stand up above the more yielding softer rocks (Fig. 72). Accordingly, the main tributaries are established upon the soft outcrops. Such tributaries are clearly not a direct consequence of uplift, they are a subsequent development; and so streams with courses adjusted to run along soft outcrops are called subsequent streams. Hard and soft outcrops often lie parallel with one another, approximately following a constant line of strike. Their course is said to constitute the grain of the country. Subsequent streams follow grain or strike.

Draw a second map and insert upon it a series of subsequent streams (Fig. 81, 2).

The third chapter introduces river capture or piracy. If for any reason one consequent stream cuts down more deeply than its neighbours, its subsequent streams also cut down more deeply and thus capture more and more of the drainage of the subsequent valley. At last, continuance of this process intercepts some neighbour consequent stream, capturing its headwaters, or in other words beheading it.

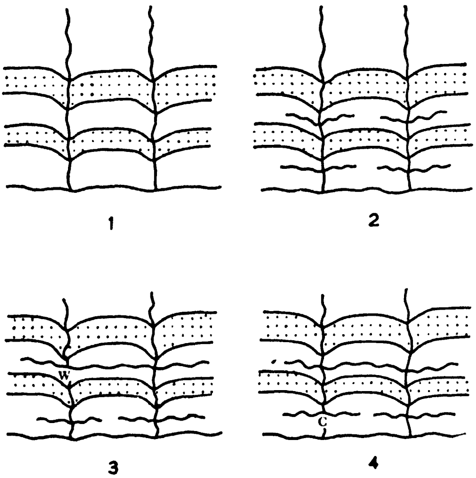


Fig. 81. River development: 1, with consequents; 2, with subsequents; 3, with beheading (W, watershed); 4, with corrom-formation causing obsequent (C, corrom).

In a third map illustrate such capture (Fig. 81, 3).

The more water a consequent stream captures, the greater is its advantage over neighbours in cutting through resistant outcrops farther downstream. Thus the process of river capture, or piracy, continues, and one consequent stream may by the help of subsequent streams capture the head waters of a large number of consequent streams. The most diagrammatic example in Britain is afforded by the Humber, with its subsequent streams situated on the soft outcrop of the Trias, the Ouse on the north and the Trent on the south.

The fourth chapter in river development concerns the fate of streams that have been beheaded. Deprived of much of their water they may be unable to keep their courses clear. Two very common obstructions may block them and furnish a watershed at some point or other. One of these is a landslip, and the other, and much more usual, is a delta built up by some tributary. An obstruction due to either of these causes may reverse the drainage in the upper part of a beheaded stream. A stream draining with reversed flow from a beheaded valley (or for that matter with contra-consequent direction from an erosional escarpment) is called obsequent.

In a fourth map illustrate reversal of drainage on a corrom (Fig. 81, 4).

A delta-watershed is called a corrom (Fig. 82). The name comes from a Gaelic word meaning a balance. It has been applied by the inhabitants of Argyll to at least two delta-watersheds built out by tributary streams, because, on issuing from the tributary valley, the water is balanced, as it were, on the delta, and may one day flow one way, and another the other. It has now been introduced into general Geology. A corrom is readily transformed into a rock watershed, through erosion due to the obsequent stream. A good example of a corrom occurring near Glasgow has been built across the through valley of Strathblane by the Ballagan Burn.

Fig. 82. A corrom, or delta-watershed, in East Lothian. The shape of the corrom, which was deposited from the small gorge on the far side of the valley, is brought out by the telegraph poles in the railway cutting. (Kendall and Bailey, 1908.)

Once a beheaded valley has developed a watershed, so that it no longer carries a continuous stream, it is called a windgap. Strathblane is a windgap. So too is the valley connecting Fintry and Denny in the same general district. So too is Gleneagles. These three windgaps are extremely interesting as they show that at one time the ridge of igneous rock reaching from side to side of Scotland, through the Kilpatricks, Campsies, Ochils, Sidlaws, did not exist as a surface feature. The Highland rivers crossed it freely, but have now mostly been captured by subsequent streams that have entrenched themselves in a belt of Old Red Sandstone sediment north-west of the igneous outcrop. This belt has been cut out into a continuous series of valleys, the eastern part of which is called Strathmore (literally translated as Great Open Valley). The story is complex, but some items are fairly clear on a geological map. The Teith, continued by the Forth at Stirling, is probably a successful consequent river; so too is the Tay at Perth. The Forth at Drymen, and more particularly the Isla, north of the Sidlaws, are excellent subsequent rivers. The Clyde may be in large measure an obsequent river: it is thought by some to carry the reversed drainage of the head-waters of the Tweed.

In areas of hard rock, shatter belts along faults may serve as guides to subsequent rivers. This is the case in the Highlands, where many of the subsequent valleys have been overdeepened locally by glaciers to furnish rock basins for lochs. The best example is afforded by the shatter belt of the Great Glen, which determines the course of the Caledonian Canal and of Loch Linnhe (Fig. 83).

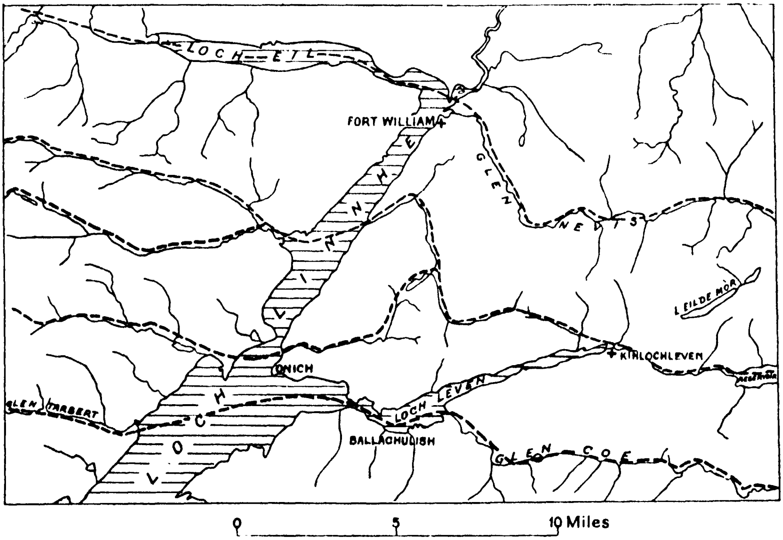


FIG. 83. Map of Ben Nevis region, showing ancient consequent west-to-east valleys segmented by subsequent valleys that have been eroded along shatter belts now occupied by Loch Linnhe and Loch Leven.

Consequent rivers need not always flow in the direction of dip, and this is one reason why it is very difficult to recognise consequent rivers with certainty. There are two main independent causes for disagreement between the direction of consequent rivers and dip:

(1) The rivers may have started on a formation which has since been entirely removed by erosion. This formation may have rested unconformably upon a previously folded and eroded foundation. When the rivers cut down to the foundation, they are naturally discordant to its dips. Such rivers are said to be superimposed. The Teith-Forth valley is an example. The radiating valleys of the English Lake District furnish others.

(2) A mountain system may be developed across the course of a river so slowly that the latter may be able to maintain its direction by cutting down as the mountain rises up. A river so situated is described as antecedent.

The phenomenon of antecedent drainage may become so impressive as to appear almost unbelievable. A river passing through the core of an anticline may have rocks of particularly resistant character exposed all the way from the floor of its gorge to the summit of adjacent rugged peaks. At first sight it seems incredible that its waters should not have been turned aside by the uplifting of so firm an obstacle. The explanation is usually to be found in soft unconsolidated sediments, long since worn away at the arch of the fold. When an anticline begins to raise a thick mass of modern marine sediments, antecedent rivers need find no difficulty in keeping their courses clear of mere clay and sand. Before the folding brings really hard rocks to the level of erosion, the rivers may be firmly entrenched in valleys thousands of feet deep, from which they cannot easily be diverted by slow continuance of earth movement.

The Indus and Brahmaputra traverse the Himalayas from north to south, and are usually interpreted as antecedent rivers.

While superimposed and antecedent drainage must be awarded the main responsibility for rivers crossing anticlines, consequent drainage must also be allowed a share in the phenomenon. For instance, in the Isle of Wight, there is a strikingly asymmetric anticline, in which a steep, or vertical, northern limb contrasts with a very gently inclined southern limb. This anticline in Mid-Tertiary times elevated incoherent Early Tertiary sediments, and it obviously cannot have produced a surface form in any way closely comparable with the tectonic form now revealed by erosion. Instead, the Early Tertiary sands and muds, contemporaneously with their uplift, must have been reduced by slip and rain-wash to a fairly symmetrical ridge with its summit well behind the tectonic crest. Thus we find the Medina, a northward draining consequent, starting from a source considerably south of the anticlinal axis.

CHAPTER XXXIV

SEA

EROSION.—The sea erodes by wave violence, which may be greatly assisted by:

(1) Pebbles used as tools.
(2) Compressed air driven into joints and cavities.
(3) Boring organisms, which attack shale and limestone.

Waves derive their power from the wind, and their effect rapidly decreases with depth, becoming imperceptible at a depth equalling the wave-length. Thus lateral corrasion plays a larger part in comparison with vertical corrasion than it does in the case of active rivers.

The sea tends to fashion hard rocks into headlands and soft rocks into bays. Except on a small scale, marine erosion will only make broad, open features of this kind. An intricate coastline such as is common in the West Highlands has never resulted from marine erosion, for marine erosion is concentrated on exposed headlands and is often replaced by deposit in sheltered sea-lochs. The West Highland coast is due to two independent causes:

(1) subsidence and drowning of a subaerially eroded valley system; and
(2) entry of the sea into valleys overdeepened by glaciers.

These two causes are very difficult to disentangle in the Highlands; but in the Devonshire peninsula, which lies south of Pleistocene glaciation, subsidence is very clearly illustrated in several examples.

Waves attacking a slope at its base tend to produce a cliff by undermining, if the rock be strong enough to stand upright, but, in softer materials, a steep slope.

As they advance waves develop a terrace or shelf of erosion, with partial inconstant cover of deposit. This shelf slopes very gently out to sea, furnishing an approximate platform. Permanent deposit gathers only below the level agitated by the waves, where it constitutes a submarine terrace of accumulation continuing the platform feature due to erosion.

Round most continental shores there is a very gently sloping shelf leading down to the 100-fathom contour. Below this the depth increases more rapidly towards the ocean. The continental shelf, as it is called, is probably in part due to marine erosion and in part to marine sedimentation. Sonic sounding has demonstrated that its outer slope is in places channelled by deep canyons due to some problematical kind of river erosion—possibly subaerial in origin, possibly submarine.

Bedding, joints and vertical crush-zones all have a great effect in shaping sea cliffs. Accordingly, these may be vertical (Figs. 44, 84), outwardly inclined or even overhanging. The overhanging attitude is the least stable, but is illustrated rather strikingly in Fig. 85, where it is shown supported by a natural buttress.

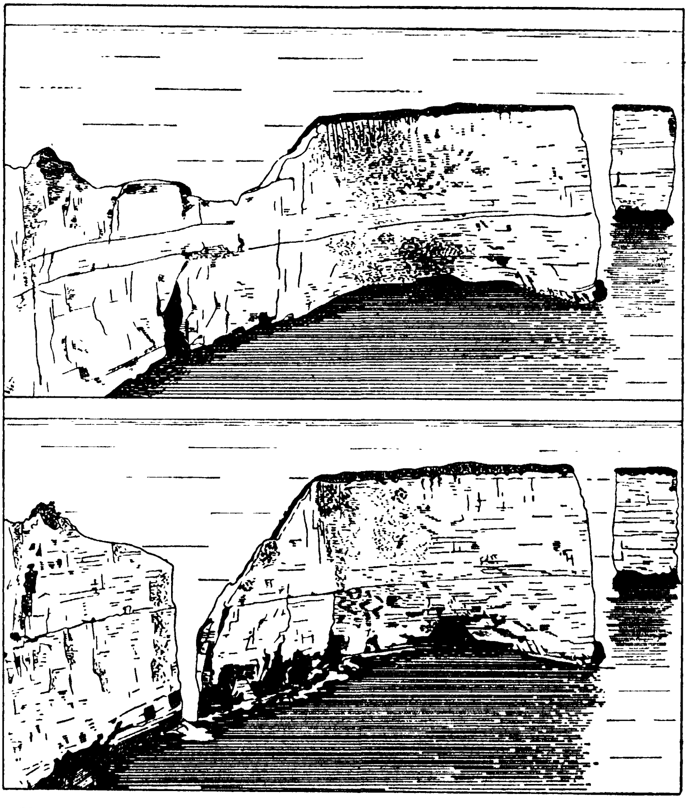


FIG. 84. Hardfast Point, near Swanage, Dorset, 1902 and 1912. (S. H. Reynolds photo.)

Often some master joint, or crush zone, leading into a sea cliff gives a special advantage. A chasm is started, and the waves directed into it act like a to-and-fro river with concentrated attack. The chasm, with its two sides, may be able to maintain a roof at a height not reached by the main force of the waves. Thus sea caves result, generally along the course of some master joint, crush or dyke. Very often the roof of the cave is determined by some bedding plane, above which a stronger formation lies, or by some limit, above which the joint system is less suitable for quarrying. This latter occurs at Fingal's Cave, Staffa, as already explained (Chapter XX).

Compressed air is specially effective in caves, and may, with assistance from collapse, form blow holes a long way inland.

Two chasms advancing along parallel joints sometimes unite, where erosion is guided by a transverse joint. The result is the isolation of a cliff-bounded islet known as a stack (Figs. 44, 84). The Old Man of Hoy in Orkney is the most famous of many British examples.

The sea may erode as rapidly as Niagara, that is about 5 feet a year, where it has to deal with soft rocks. Elsewhere its progress is generally slow.

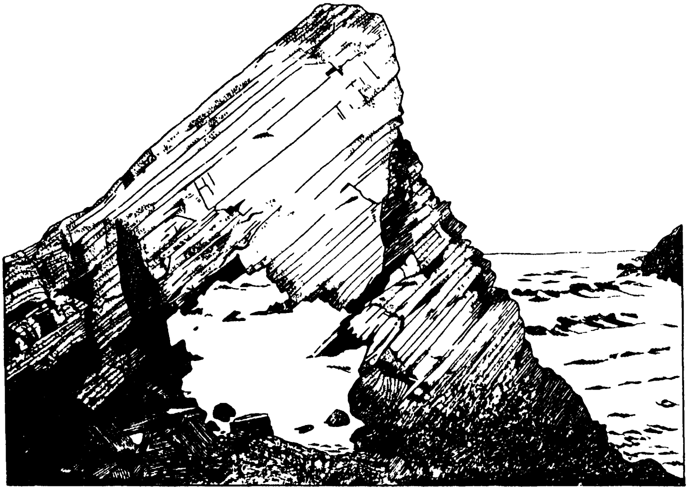


FIG. 85. The Needle Eye Rock, near Macduff, Banffshire. Joints incline towards right.

MECHANICAL SHORE DEPOSITS.—Erosion and transport are always interrelated. Some load helps wave erosion by furnishing tools; but load provided at one part of a coast frequently gives protection to another part, and even builds it out seaward.

There is a tendency to sort the coarser material towards the shore owing to the greater strength of advancing waves. This explains the frequency of gravel beaches. Mud is only dropped in sheltered estuaries or in fairly deep water. Thus the zone of wave action is typically bounded by shingle, reaching above high water, and by mud, reaching below the level that is subject to disturbance.

Waves are greatly helped in transporting boulders by ice or sea-weed. It must always be remembered that immersed boulders lose much of their effective weight through buoyancy.

Where a wind blows obliquely on a shore it sets up a pulsating zigzag current along the shore carrying sediment as coastal drift. The general direction of a shore current is parallel with the deflecting shore. Where the shore is indented the current tends to carry on straight, and to drop its load on reaching deeper water, thus building a spit. The process is cumulative, for after the spit has started to grow it guides the coastal current ever farther in its straight course. A spit may be built by degrees right across an inlet so as to enclose a lagoon. It may also rise above high-water through additions of shingle and blown sand. Spits with lagoons are common in Scotland, particularly in Orkney. Spits on a larger scale figure very prominently in Holland and along the Atlantic shores of the U.S.A.

A very usual coastal feature is a spit built out to connect an island with the mainland. Material carried shoreward accumulates in the shelter of the island.

Rivers bringing their detritus to the sea often drop it at their mouths to form a bar. A river may sometimes be forced to dredge its own bed, by artificially confining it in its estuary to a single course. Many bars are added to by coastal drift. On the other hand accumulation of a bar may be prevented where the coastwise current is underloaded.

Any interference with a coast line may affect the balance between erosion and deposit for very many miles on the lee side of the interference. Thus a groyne, built out at right angles to a shore, by retaining the drifting sand on the one side may institute active erosion on the other. Near Los Angeles a highly-prized bathing beach has been ruined on the lee side of a recently constructed swimming pool

In tropical seas, on the east coasts of continents and in mid ocean, coral reefs are a characteristic feature (Fig. 86). These reefs may be :

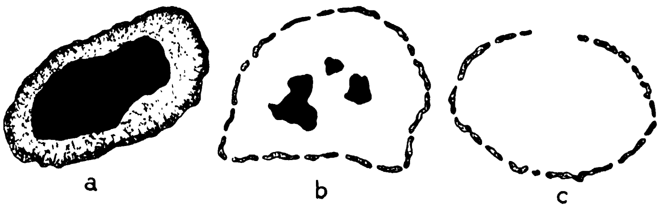


Fig. 86. Maps of coral islands.
a, fringing reef ; b, barrier reef ; c, atoll.

(1) Fringing, where attached to the main coastline.

(2) Barrier, where they stand away from the main coast. The Great Barrier Reef of Australia is 1,200 miles long and lies 25 miles off-shore with a depth of 100-300 feet in the intervening channel.

(3) Atoll, where the reef forms a roughly circular ring about a lagoon, which may be 200 or even 300 feet deep. Such an atoll may be anything from 2 to 50 miles across.

Coral only grows to a little above low water. Coral islands may result from storm beaches and blown sand built upon a reef, or from elevation of a reef. The name is also loosely applied to volcanic or other islands surrounded by coral reefs.

Corals only grow luxuriantly in exposed positions, where the waves bring them food. Mud is fatal. Depth also is fatal. Reef building corals do not grow at depths of more than 250 feet. As the waters immediately outside coral reefs are commonly of much greater depth than this, we are faced with a problem. Two explanations have been offered, the first by Darwin, recently modified by Daly, the second by Murray.

(1) Darwin suggested that coral reefs start in shallow water as fringing reefs. Then, if gradual subsidence takes place, they grow almost vertically upwards along their exposed rims, and so become barrier reefs, well in advance of the shore, which necessarily retreats with submergence (Fig. 87).

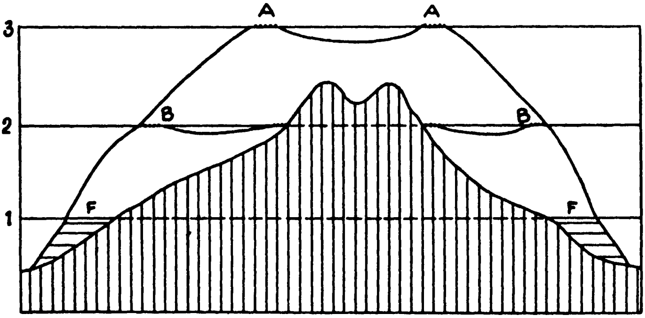


FIG. 87. Darwin's submergence theory.
F, fringing reef; B, barrier reef; A, atoll.
1, 2, 3, successive positions of sea-level.

Later, with continuance of subsidence, the shore, if it belongs to an island and not a continent, may be carried completely under water, leaving the barrier reef, still growing, transformed into an atoll. Darwin's beautiful theory has been supported by a bore at Funafuti Atoll, in the Indian Ocean, which passed through 1,000 feet of coral rock without reaching bottom. If it had been possible to demonstrate that any of the corals towards the bottom of the bore were in position of growth, his interpretation would have been definitely proved in this particular case. His opponents, however, claim that the bore passed down through consolidated coral debris. Be this as it may, support is furnished to Darwin's theory by the observation that the valleys behind the Great Barrier Reef of Australia are in an obviously drowned condition, indicative of submergence.

Daly's modification of Darwin's theory is as follows: He contends that the lagoon depth of the atolls and barrier reefs is so consistent that it points to a world-wide rise of oceans, rather than a local subsidence of lands. He has calculated the volume of water that must have been locked up in the glaciers of the Ice Age, and considers that it would account for a 300-feet lowering of sea-level. He thinks that many coasts were cut down to a corresponding low level by wave and other erosion, especially as the cooler seas of the time would slow down protective coral growth. Finally he pictures post-Glacial return of water, at a genial temperature, as affording the corals a splendid chance to convert shoals in process of submergence into atolls.

(2) According to Murray's theory the corals of atolls begin on shoals, furnished, for instance, by eroded volcanoes. Starting at very moderate depth, they reach the surface and expand outwards as a ring, due to the active growth of the wave-washed outer members. Submarine scree from the front of the reef supplies the foundation for this outward growth. The corals of the centre die, and, exposed to boring and solution, pass into coral mud, which is carried out to sea through gaps in the reef. There is always a current setting out from a lagoon, during storms, to carry off the water of the waves that break over the reef. Thus Murray pictures the lagoon as an erosion feature, not a subsidence feature.

Probably Darwin's theory, or Daly's modification, accounts for some atolls, and Murray's for others, especially the comparatively small rings that are found, for instance, along the course of the Great Barrier Reef. There is fine scope for some millionaire to sink his money in search of the foundations of these mysterious fairy circles.

CHAPTER XXXV

DESERTS AND STEPPES

DESERTS have been defined as regions with less, often much less, than 10 inches of rain per year.

They are regions of internal drainage. Their rivers dry up in the open, or discharge into lakes without outlet. Occasionally a big river, like the Nile, may cross a desert ; but it is supplied from outside.

The position of deserts is largely influenced by distribution of land and sea, and of mountain chains ; but in a broad way the deserts of the world fall into two main belts, north and south of the equatorial rains. The Northern Belt includes the Sahara, and stretches east through Arabia into Mongolia ; in America it claims the Great Basin with the Great Salt Lake. The Southern Belt embraces the Kalahari desert in Africa, much of Australia and part of South America.

EROSION.—Desert erosion is perhaps (opinions differ) a comparatively slow affair. According to this view the rarity of water as an eroding agent is not fully compensated by the sparsity of vegetation as a protective covering. At the same time, nowhere else on the earth's surface is there such diagrammatic evidence of erosion as in a rock desert. This is due to the fact that the wasting of detached material, through removal by wind or rain, generally keeps pace, approximately, with the breaking up of solid rocks. The result is that a rock desert furnishes an amazingly clean workshop for weathering effects. Every rock is attacked according to its own merits ; the soft cannot shelter beneath the debris of the hard. Also every structure, such as bedding or jointing, has a full chance to guide erosion (Figs. 72, 88). Scarps and pinnacles are characteristic, dependent upon the predominating influence of stratification or jointing. As already emphasized, flowage and landslipping disappear.

The main weathering agents of a desert are :

(1) Rain, which though infrequent produces very marked effects owing to absence of vegetation. Many rock faces in deserts are channelled by rain-wash. In such a case it is clear that other agents have not had sufficient power to obliterate the marks left by one shower before another intervenes.

(2) Insolation, which has already been discussed.

(3) Crystallization of salts sucked up in solution to near the surface by capillary attraction accompanying evaporation. The crystallization of such salts in the pores of a rock tends to disintegrate the rock and render it friable.

(4) Oxidation, which is very active where water and air act without the reducing tendencies of vegetation. Iron and manganese salts sucked out on to the surface of rocks, and perhaps distributed by splashing rain, oxidize to ferric oxide and manganese dioxide, to give a dark shining coat that is called desert varnish.

FIG. 88. Erosion in the semi-arid Bad Lands, South Dakota. (Lease photo.)

In fairly moist deserts, such as the Sudan and parts of Arabia, ferric oxide is formed as a film on the loose sand grains, thus providing red deserts. It was under such conditions that much of the New Red Sandstone of Britain formed. The oxidation of iron may continue far below ground. Thus in Arran the floor of the New Red Sandstone desert is reddened and oxidized for 500 feet below the desert deposits. Similarly the copper sulphide ores at Butte, Montana, an arid district, have been wasted by oxidation to soluble sulphate to a depth of 500 feet.

Wind is the most important agent of transport at any rate in thoroughly dry desert regions, and is responsible for considerable corrasion. Like the water of humid regions it requires tools to be really effective against consolidated rocks. Its sand-blast decreases in intensity a short distance above ground level. Thus telegraph posts need special protection at their base, and upstanding rocks are often undercut. On a larger scale the mountains of desert regions may escape with little sand-blasting. Rock surfaces in the Red Sea mountains are soft and crumbly.

Wind erosion is more widespread than river erosion. It may hollow a depression, but it does not dig a valley with tributaries. In its effect upon a rock surface it smooths and polishes, where the rock is uniform, and develops inequalities, where there is stratification or any other guiding structure. Sand-blasted conglomerate on the shores of Arran shows pebbles etched out as wind-moulded projections with tails of matrix protected in their lee.

DEPOSITS.—Many of the loose pebbles of a desert are angular in form, though with polished and wind-moulded surfaces. They are called dreikanters, which means in German three-cornered, but the exact number of corners does not matter. Some owe their angles to sand-blasting, combined with intermittent overturn, which exposes a new surface to attack (Fig. 89). Artificial dreikanters can be produced in this manner, experimentally, from pebbles of any original shape (W. H. Schoewe, *Am. Journ. Sci.*, ccxxiv, 1932, p. 111). In other examples, which possibly do not fully deserve the name dreikanter, the flat faces are fracture faces, due perhaps to insolation. In such cases the angles have not been produced by wind erosion, but have merely been left alone. The only thing that the wind has done is to etch and polish the surface (W. H. Hobbs, *Acad. Sci. Rep.*, 1918, 20th March, p. 95).

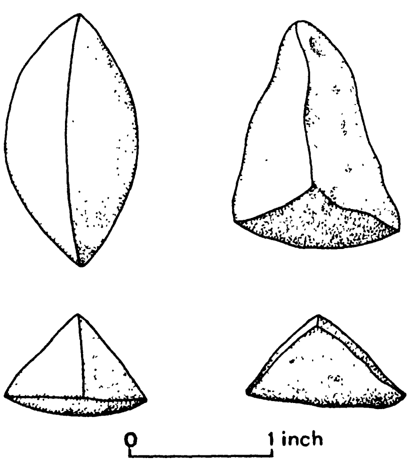


FIG. 89. Dreikanters in plan and elevation.

While the stone pebbles of deserts tend either to be made, or left, angular, the sand grains tend to be rounded, even at quite small diameters, at which water-rounding becomes inefficient. Rounded sand grains proclaim desert conditions during the formation of the British New Red Sandstone, and have also allowed us to recognise that the Chalk Sea had a desert shore.

Sand is the great deposit within deserts, and dust around their margins. Sand accumulates in travelling mounds or hills called dunes. In longitudinal section a dune presents a gentle slope to the wind, up which sand is driven. It has a steeper lee slope, down which sand slides, and beyond which complicated eroding vortices are produced in the wind current. In plan, dunes vary greatly, according, it is here suggested, to the strength of wind in relation to the supply of sand :

(1) If the sand-supply is very abundant compared with the wind the

dune forms a ridge at right angles to the wind, though with projections on the lee side pointing with the wind. Such a condition is often found in our own country just on the landward side of a sea beach. On a minute scale, ripple marks may be grouped under this heading.

(2) If the wind and sand-supply are balanced the dunes become isolated crescents. The horns of the crescents are due to a sideways diversion of the bottom current of the wind.

(3) If the wind is overpowering, the dunes become ridges parallel with the wind.

On coasts, sea sand, exposed at low tide without cover of vegetation, is often blown inland to give shifting dunes. In Europe, the sands of the Bay of Biscay afford the main example ; and, in Britain, the Culbin Sands of the Moray Firth. The Culbin Sands at the present time completely hide the Culbin Manor House. They also march slowly through woods burying and killing them, and then passing on. A common effect with blown coastal sands is to dam streams and form lakes. Planting with bent (a particular form of grass with very extensive rhizomes) is undertaken to tether destructive dunes. Trees of suitable character are also employed.

The internal features of dunes are large-scale current bedding coupled with small-scale ripple marks. These features reappear in fossil dunes of our New Red Sandstone.

The temporary rivers of desert regions cut gorges, where the slope allows ; but they tend to dissipate by evaporation and absorption, especially on level ground. This leads to the formation of distributaries building extensive dry deltas made up of intensely irregularly bedded accumulations of pebbles and sands. Oases occur where the ground-water of such deltas is discharged at the surface by some impervious layer. Many of the conglomerates of the Old and New Red Sandstones were formed by temporary rivers wandering over a desert land surface.

Where desert rivers discharge into lakes without outlet, evaporation leads to concentration of salts. This subject has already been considered under the head of Chemical Sediments (Chapter XV).

Salts are deposited, not only in lakes, but also locally on dry land. This happens where the water table is sufficiently high to allow water to be drawn to the surface by capillarity. There results what is called alkali desert (the term alkali is here used incorrectly to include neutral salts like NaCl as well as true alkali salts, such as Na_2CO_3). Alkali deserts are particularly bad for plant life. In most irrigation schemes it is essential to arrange for drainage of ground water. If all the water added by irrigation is dissipated by evaporation alkali desert follows, perhaps slowly, but at any rate surely. It must also be borne in mind that there is a danger of irrigation water connecting in depth with saline ground water and thus helping previously deeply buried salts to reach the surface.

The preservation of footprints in desert sandstones is probably often due to a thin surface layer of gypsum, which is ideally suited to retain an impression, because gypsum is the basis of plaster of Paris.

The shore line of a lake without outlet depends upon the balance between rain and evaporation. If the rain increases the lake expands, and vice versa. Thus old shore lines furnish records of old climates. The past history of the Great Salt Lake has been studied in detail. In a former rainy, or pluvial, period, as it is called, the lake was very much bigger ; and, as its outlet can be recognised, the water must have been fresh. This pluvial period corresponded with part of the Pleistocene glacial period of more northern climates.

LOESS.—Stretching across much of northern Europe into Asia, from France to China, and reappearing in the Mississippi valley, is a fine-grained unstratified yellow to brown loam known as loess. It is generally under 100 feet thick, except in China, where it may be 1,000 feet thick. It is soft enough to dig, and yet is vertically jointed, and is sufficiently compacted by calcareous cement to maintain vertical cliffs, where attacked by erosion. It is thickest in valleys, but, unlike flat-topped alluvium, it rises gently up hill slopes to mingle with scree. The fossils of loess are few, but include land snails, jerboa, etc. Another feature is supplied by calcareous concretions, which grow vertically, something like the cornstones of the Old Red Sandstone. Loess is interpreted as a dust deposit, anchored by sparse grass, which has prevented the development of bedding. The vertical roots have left innumerable vertical tubes to which the characteristic jointing is due. Loess is forming to-day on modern semi-arid grasslands called steppes. The great trans-continental development, to which reference has been made, belongs to the Ice Age. It formed when wide spreads of glacial deposits lay unprotected by vegetation, so that their dust was easily blown outwards to neighbouring grass-lands. Loess is very sparingly developed in Britain, but is probably represented among the Thames Valley brickearths.

The yellow colour of the loess is responsible for the name Hoang (yellow) Ho (river). The Hoang Ho flows over great loess deposits and carries its load into the Yellow Sea.

Many Chinese live in houses dug out of loess. As already stated the material is both soft and durable.

CHAPTER XXXVI

GLACIERS

A MASS of flowing ice is called a glacier. It may vary in area from a fraction of a square mile to many hundreds of thousands of square miles.

Glaciers are fed by snow. Semi-compacted snow in the half-way condition to glacier-ice is called *névé*.

Glaciers exist wherever annual snowfall is in excess of melting and evaporation. Such regions are said to lie above the snowline, which may be 18,000 feet above sea-level in the tropics, or right down to sea-level towards the poles. The snowline depends, not only upon temperature, but also upon precipitation. Many cold regions receive too little snow during the course of the year to allow of any surplus escaping melting or evaporation. Siberia, with its frozen mammoths, has no glaciers.

Mountains, with their cold upper regions and their abundant precipitation, provide good sites for glaciers. It may be mentioned that winds are cooled in going over mountains, not so much by conduction, as by expansion due to rising into regions of low pressure. Any gas, when expanded, cools—the principle employed, for instance, in preparation of liquid air.

Except in polar regions, modern glaciers are only found among mountains, where they are largely fed by wind-drift and avalanche. The characteristic form is the valley glacier, a true river of ice. Such a glacier moves much more slowly than a water river ; it fills a much larger proportion of its valley at any one point ; its tributaries are fewer ; its maximum length is less—about 10 miles in the Alps and 50 miles in Alaska.

Sometimes in Alaska important valley glaciers unite beyond the mountains to form a spread of ice known as a piedmont glacier.

With increase in size, valley glaciers coalesce above the walls of their valleys, giving a great mass with gently domed surface and with radial outward flow. Such masses, with an area of perhaps a few hundred square miles, are called ice-caps, of which there are good examples in Iceland. They depend for nourishment upon the snow that falls on their own surface.

Mountain tops, projecting island-wise through glacier ice, are called nunataks.

Ice-caps of the largest size are termed ice-sheets, or continental ice-sheets. At present only two examples occur ; one in Greenland, the other in Antarctica. During the Pleistocene, two other huge ice sheets existed, the Brito-Scandinavian and the Canadian. This statement records one of the most surprising discoveries of Science. It is interesting to recall that the former glaciation of Britain was first definitely announced during a meeting of the British Association held in Glasgow in 1840. We shall return to this subject after describing some of the characters of modern glaciers.

Valley glaciers are far more numerous than other forms, though their aggregate bulk is comparatively trivial. They were first studied in the Alps. They obviously flow, since in spite of melting they reach far below the snow-line. Measurements of velocity are taken by planting a row of stakes across a glacier. These indicate swifter movement in the centre than at the friction-impeded sides. The velocity of a big Alpine glacier is 2 feet a day. The Greenland ice-sheet in its interior portion only flows about 1 inch a day, but near the edge it feeds valley glaciers that escape through portals in the border mountains at the rate of 50 to 100 feet a day.

Ice flows much as though it were a viscous fluid ; the precise physics need not detain us. The direction of flow is approximately determined by the slope of the upper surface of the ice, for bottom layers are dragged along by the freely moving upper portion. Bottom flow is not directly observable, but can be deduced from scratches, or striae, produced on the underlying rocks, if these are exposed to view by subsequent melting of the ice (Fig. 1). Such striae are the work of stones and grit dragged along at the bottom of the ice ; ice, like water, requires tools for effective grinding. Striae formed at about the same time on a particular rock surface are approximately parallel. Loaded ice passing over a rock face often moulds and polishes it, as well as scratching it. The commonest effect is to smooth away any little obstruction that faces the ice flow. This is very important in reading the direction of ice flow from striated surfaces. Suppose the striae run E. and W. This shows that the ice flow was either towards the E. or towards the W. Putting one's eye near the surface, one looks first east along it, and then west. In most cases the surface will appear as smooth curves when one looks in the direction of ice flow, but will be broken by a series of steep unsmoothed little slopes when one looks against the direction of ice flow. In geological maps glacial striae are shown by the sign -⊖→, with the arrow head pointing in the direction of flow. If the moulding is not clear enough to indicate this direction, a headless sign is employed -⊖-.

The same type of moulding is often seen on a much larger scale where an upstanding rock, several yards long, has been glaciated. The result is called a *roche moutonnée* : Many books give a wrong derivation for the name, saying that *roche moutonnée* means a rock that looks like a sheep. The true meaning of *moutonnée* is fleecy, in the sense in which we use that word in the phrase fleecy clouds. A group of *roches moutonnées* gives a surface with an up and down arrangement like that of a fleece.

To return to the shape of an individual *roche moutonnée*. The smooth front is determined by the grind of the over-riding ice. The rough back is due to the pluck of the same ice as it passes on its way. Ice does not erode solely by grinding. It often pulls up fragments big or small from its floor, separating them along joints. On the front side of a *roche moutonnée* this pulling, or plucking, action is checked by push; but on the rear, or lee, side the push is not felt and plucking becomes very important.

Where the rock mass that is traversed assumes the dimensions of a hill, of say a mile in length, the characteristic form of glacial erosion changes round about; there is a steep front and a gently sloping back. This form, where the steep front is composed of solid rock, is called crag and tail. Often the crag front is made of some particularly hard rock, and the tail consists of softer rock, in some cases glacial deposits. The finest example of crag and tail in the world is afforded by Edinburgh Castle Rock, as crag, and the Royal Mile leading to Holyrood Palace, as tail. The Castle Rock is a cylindrical plug of basalt marking the site of a volcanic pipe. The rocks round about are much softer sandstone and shale. The ice-sheet was flowing towards the east. Its top was far above the top of the Castle Rock, but its bottom currents were deflected to the north of the rock, where they gouged out the valley of Princes Street Gardens, and to the south of the same, where

FIG. 90. Terminal curvature caused by passage of ice-sheet, Riston, near Blackburn. (J. Ranson photo.)

they gouged out the valley of the Grassmarket, now crossed by two bridges carrying high-level roads.

Where the rocks are yielding, glacial flow may induce superficial bending and even folding. It is not infrequent to find phenomena comparable with surface creep, where glaciers have deformed steeply dipping strata (Fig. 90) or slaty cleavage. Contortion due to this cause is particularly striking in certain glacial deposits of East Anglia and Denmark.

Striae and associated moulding afford some of the most convincing evidence of the past extension of glaciers. They are found in perfect freshness at the ends of Swiss and other glaciers, often in positions known to have been covered by the glaciers only a few years ago. On hard rocks, or where they have been sheltered by clay or standing water from the effects of weather, they are still preserved all over Switzerland, showing that at one time that country was completely covered by an ice-cap. Similarly they occur in plenty in Britain and northern Europe, and, together with other evidence, indicate that during Pleistocene times a great ice-sheet enveloped the British Isles as far south as the Bristol Channel and the northern suburbs of London. This ice-sheet was continuous across the North Sea with Scandinavian ice that reached southwards far into Germany.

The records of vanished ice-sheets show that the slope of the upper surface of an ice-sheet has much more importance in guiding the bottom currents than the form of the bottom itself. Scottish ice escaping to the Atlantic crossed the Kintyre peninsula almost at right angles, as shown by numerous striae which rise up the slope without deflection.

CHAPTER XXXVII

GLACIERS (*continued*)

GLACIERS generally start upon a land surface already shaped by river erosion and weathering. It is interesting to summarize the more striking modifications they introduce in such parts of their course as they erode.

Weathered material is stripped off, and the solid rock below is striated and often moulded into *roches moutonnées* and crags with tails. The direct erosive power of a glacier is generally much more widespread than that of a river. Where the glacier is an ice-sheet the whole surface of the land may be ice-eroded, as illustrated by the rock furrows in the neighbourhood of Edinburgh ; even where the glacier is confined to a valley it occupies a large part of that valley, and is not restricted merely to a river bed at the very bottom.

The big size of glaciers is correlated with their slow motion, which has allowed the glaciers to grow for a long number of years, until the discharge of the glacier equals the snowfall of its drainage area. While the glacier grows it is accumulating pressure, and this gives power to its grinding, despite the slowness of its movement. There is practically nothing equivalent to this factor in ordinary river action.

A glacier occupying a V-shaped valley opens up the V into a U, because it occupies so much of the valley and moves relatively slowly in the constricted bottom portion of the V (Fig. 91).

A U-shaped valley, though with flatter base, may also be produced by the meandering of a graded river, and it may be difficult to decide in certain cases which cause has been responsible.

The development of a U-shaped valley cuts back the lower courses of tributary valleys, so that these cease to be concordant with the main valley, but open somewhere perched up on its side. Thus it is characteristic of glacial erosion to cause hanging tributary valleys (Fig. 91). This happens even where the tributary valleys carry tributary glaciers, for a small glacier has much less eroding power than a big one.

It will be remembered that a young or a rejuvenated river often leaves its tributaries hanging, but this is generally at the side of a canyon rather than of a great U-shaped valley.

A glacier is much less easily deflected than a river and tends to erode away any obstructing spur. Thus we find truncated spurs between the hanging tributaries of U-shaped valleys.

Similarly where a glacier flows across a watershed it may grind it down and give a through valley.

A very common feature of glacial erosion is the cutting of rock basins. Rivers can only cut relatively shallow basins and potholes. As soon as they begin to make a considerable hollow their current is lost, and they deposit sediment instead of eroding. Rivers are busy to-day obliterating the lakes of Scotland and the Lake District, not digging out new basins. A glacier owing to its slow motion may retain a considerable gradient for its upper surface even when its lower surface occupies an enclosed basin ; and, as already pointed out, it is the flow of the upper layers that drags forward the lower layers. Moulding and striae show conclusively that bottom ice may erode effectively even when moving uphill. Thus a glacier can cut out a rock basin. In fact a glacier definitely tends to do so, even where the nature of the rock bottom is uniform. A glacier has no eroding power at its snout, while it does have eroding power farther upstream.

FIG. 91. Glen Nevis, a glaciated valley with U-shaped cross-section, truncated spurs and hanging tributaries.

It is demonstrable that many of Scotland's greatest lakes occupy rock basins. An extremely clear example is afforded by Loch Coruisk in Skye, at about 25 feet above sea-level. It has a depth of 125 feet and a bare ice-moulded rock-barrier. Loch Morar, the deepest lake in Scotland, stands at about the same height above sea-level, and has a depth of slightly more than 1,000 feet. Careful search shows that it too occupies a rock basin. The only alternative to ice-erosion is earth movement, but most people regard it as certain that Scotland has not been folded in recent times in a sufficiently complicated manner to account for the rock basins of its lakes.

Many of these basins run along lines of fault, as Loch Ness along the Great Glen Fault. This is due to the ease with which the glaciers have removed the shattered rock.

The Great Lakes of America are situated on outcrops of soft rock bordering a very extensive interior area of hard rock from which ice passed outwards in all directions, presumably underloaded with rock debris. Their basins were probably ice-eroded, since in no other way can we account for their preference for the outcrops of soft rocks. Earth movement would not be so selective.

Glaciers can push back the sea and erode below sea-level so long as the water is not deep enough actually to float them. Many fiords owe their origin to glacial erosion. They are often much deeper inland than near their mouths.

Erosion of corries will be considered later when crevasses have been discussed. Meanwhile, as the sea has been mentioned, it may be pointed out that glaciers on arriving at the coast continue to creep forward till they float at their end and give icebergs. A special case occurs in the Ross Sea of the Antarctic. There land ice pushes out to supply a tremendous apron of ice, which, though floating, holds together for very many miles. The sea under the floating portion melts the base, while fresh snow adds to the top. At the sea margin none of the original glacier is left, so that here the Ross Barrier, as it is called, seems to consist entirely of consolidated local snow. It is certain that the Ross Barrier is afloat because :

(1) Its height above water is too little to allow of its submerged portion reaching the deep bottom which has been sounded.

(2) It rises and falls with the tide, so as to give the appearance of there being no tide along its margin.

While glacier ice to a large extent flows like a viscous liquid, it cracks like a solid when pulled. The cracks are called crevasses and are a great source of danger to travellers. They may be as much as 20 feet broad and hundreds of feet deep.

The bergschrund is a crevasse that forms and reforms at the head of a glacier between ice and rock. It is due to forward slipping of the ice, and is analogous to the landslip fissure that forms, wholly in rock, at the head of an incipient landslip.

Transverse crevasses occur wherever there is an increase in the slope of the bed of a glacier. They lie at right angles to the glacier length.

Marginal crevasses form at the friction-impeded edges of glaciers, and point upstream at about 45°. They result from the retardation of the ice at the margin. Suppose we mark out a square on the surface of a glacier, with two sides parallel with the edge of the glacier. The side that is farther out in the glacier will advance somewhat faster than the side near the rock. A little consideration will show that this leads to elongation of the diagonal of the square that points downstream from the margin. Therefore tension-cracks form at right angles to this line and point upstream.

Longitudinal crevasses develop at right angles to the margin of a glacier, where it fans out on level ground.

Crevasses, other than longitudinal, often close up fairly soon. In the case of the bergschrund the crevasse is filled up with fresh snow, which passes to ice. In the case of transverse and marginal crevasses the closure may be brought about by growth of pressure.

We are now in a position to discuss corrie formation. Glaciated valleys characteristically start as great amphitheatres, open on the down-stream side and known in Scotland as corries (Fig. 92). In their production the formation of the bergschrund is of great importance. Each time the glacier slips a few feet forward to renew the bergschrund it plucks material from the slope at the back and tends to develop it in amphitheatre form. Also, a glacier at its head is supported on three sides, instead of two. This makes the ice unusually deep and unusually persistent, so increasing every aspect of its erosion power. Thus while the upper slopes of a corrie wall are often rough through plucking, the lower slopes are often particularly moulded by grinding. For instance, a shallow rock basin is a common feature of a corrie floor.

FIG. 92. The corries of Braeriach (4248 ft.) in the Cairngorms as seen from Ben Macdhui. (Scot. Mount. Club photo.)

Most of the corries of Scotland face north-east. This is partly because a north-east exposure is cold and favours retention of snow. It is also partly due to the prevalent wind from the south-west, which leads to accumulation of snow on sheltered north-east slopes.

Even though crevasses may eventually close up, they frequently pass through a stage in which they are widely opened by thaw. They then entrap debris that has fallen on the top of the ice, and also streams that have formed on the surface. The thaw-rivers of a glacier behave very much like the rivers of a limestone country. They tend to disappear and to flow in tunnels at the bottom. Where they leap down a crevasse, or even in their general under-ice course, they may give rise to potholes, sometimes of giant size, which, if the ice melts away, seem entirely out of place.

CHAPTER XXXVIII

GLACIAL DEPOSITS

Deposits directly laid down by glaciers are called moraines :

Ground moraine consists of material dragged along, or near to, the bottom of a glacier.

Terminal moraine is the material delivered at the end of a glacier. It is largely the outer edge of the ground moraine, but contains in addition anything carried in, and on top of, the glacier. Melt-water generally co-operates to some extent in the delivery of the morainic debris. The terminal moraine of a valley glacier is often a well-defined crescentic ridge (Fig. 93) ; this happens where movement in the glacier continues right on to the melting end. In many cases, however, melting is distributed over a wide terminal zone of stagnant ice, which, belonging originally to the lower layers of the glacier, is full of stones and mud. Such distributed melting gives hummocky moraines, with holes called kettle holes. The hummocks mark where lakelets have been filled up with slipped stones, etc. ; and the kettle holes mark where ice has melted away from between such blocked up lakelets. Hummocky terminal moraines are characteristic of many Highland glens, as at Crianlarich, and are forming to-day at the ends of certain Alpine glaciers.

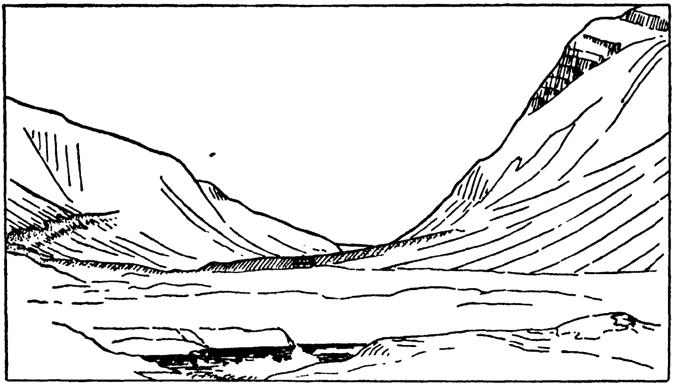


Fig. 93. Terminal moraine in a Highland glen, S.W. of Strath Conon. (Geol. Surv. photo.)

LATERAL MORAINE consists of material deposited by, or carried on, a valley glacier near its sides. There are two rather different types of lateral moraine in the Alps, lateral ground moraine and lateral top moraine. In many of the valleys there are high rampart moraines belonging to a recent advance period, in the 20's of last century (*cf.* Fig. 94, from Canada). These ramparts are generally continuous with well-marked crescentic terminal moraines, and it may be claimed that they derived most of their material from below the glacier, and that they are essentially the side limits of the ground moraine. For more than a century now the Swiss glaciers have been shrinking within these marginal deposits, which now overlook them from above. Accordingly debris from the ramparts to-day slips back on to the surface of the ice, and gives rise to the second type of lateral moraine, a thin cover of blocks and stones and grit carried on the upper surface of glaciers near their edges. It is commonly stated in books that lateral moraines derive their material from screes, avalanches and landslips shot down on to the top of a glacier from the valley sides. It seems certain, however, that this explanation is for the most part wrong in relation to the rampart lateral moraines formed during periods of glacial advance. Typically these moraines steeply face the outside scree slopes, and may for miles be separated from them by diverted streams. The relationship is particularly significant where a nunatak is surrounded by lateral moraine, for it is impossible in such a case to suggest that the moraine has been supplied by some unseen scree farther up the valley.

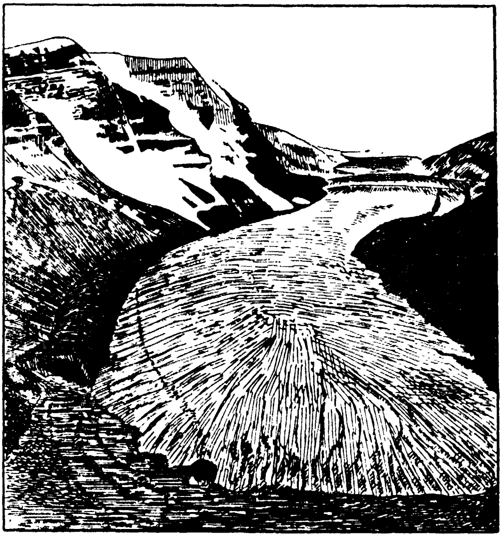


FIG. 94. Athabaska Glacier, Rocky Mountains, with deserted lateral moraine of rampart type. (National Parks photo.)

MEDIAN MORAINE is any moraine carried along the middle of a glacier. It generally results where two lateral moraines unite. It is clear in some cases that a median moraine, carried along on top of a glacier, has not derived its material from above. For instance, some median moraines start over submerged rocks that have directed ground moraine to the surface.

To return now to ground moraine. The ground moraine of an ice-sheet often consists of boulders set in unstratified clay, in which case it is commonly called boulder clay. Many of the boulders and pebbles are far-travelled, and have their angles rounded off and their faces smoothed and striated. Where a glacier traverses a sea bottom it picks up shells along with stones. In several places in Britain boulder clay contains sea shells, and has been claimed on this account as a marine deposit, with boulders dropped in by icebergs. In many cases, however, it can be shown that:

(1) The striae on the rocks beneath are too regular to be due to icebergs.

(2) The distribution of shells is determined by direction of ice currents and not by the height of the land. Thus it may happen that shells along a particular course cross high land and avoid neighbouring low land.

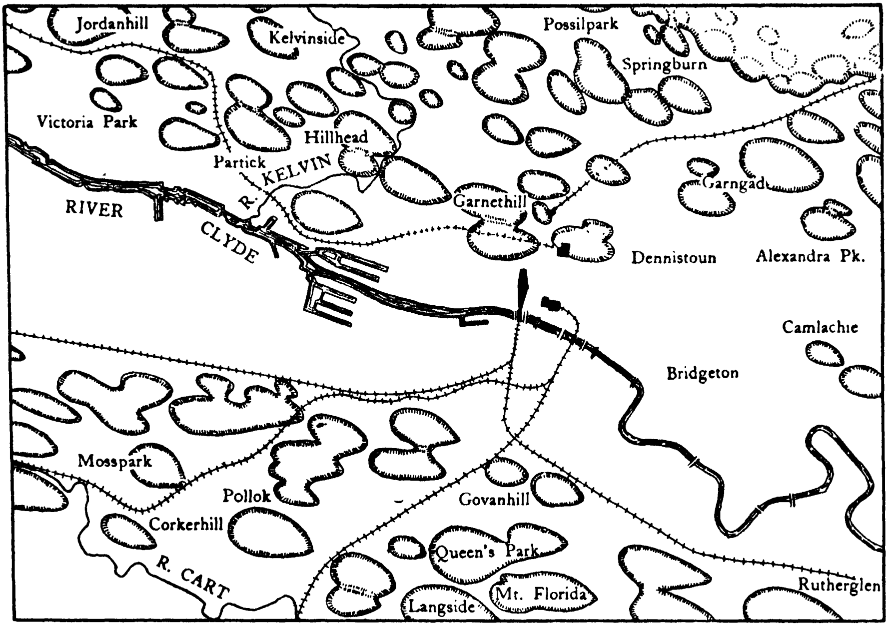


FIG. 95. The drumlins upon which Glasgow is built, due to ice flowing south of east. Along the course of the Clyde, they have been washed away. (After Elder, McCall, Pringle and Neaves.)

(3) The condition of the big strong shells shows crushing, not sea wear. Thus *Cyprina islandica* is almost always broken in boulder clay, even though it still retains its epidermis. On the other hand this strong shell exposed to wave action on the seashore remains unbroken, though stripped of epidermis and much ground down.

Boulder clay may be deposited in a uniform sheet. Under other conditions of movement and pressure, it may be shaped into a series of hills like half eggs with the blunt end facing the direction of ice flow. These hills are drumlins. Glasgow is built among drumlins (Fig. 95): Gilmorehill, carrying the University, is a small semi-detached drumlin, connecting with the Hill-head drumlin. Sauchiehall Street separates Garnethill drumlin from Blythswood Square drumlin.

Boulders or pebbles that are made of rock different from that of the district in which they occur are called erratics, meaning wanderers. The most striking examples of erratics have been transported by glaciers or floating ice. Glacial erratics may be of great size and may be hundreds of miles from their parent rock. The distribution of glacial erratics has been of the greatest service in tracing the course of Pleistocene glaciers. Thus there are very many erratics of Highland origin in the Glasgow district, including schistose grits and a porphyritic granite from Glen Fyne. Highland erratics can also be followed far into England. Similarly, in the east of England, Scandinavian boulders are numerous. In Scotland the local ice currents were strong enough almost completely to ward off the Scandinavian invasion.

Glacially transported boulders, when glaciers melt, are apt to be stranded in precarious positions on hill tops and sides, and are then called perched blocks.

The rivers connected with glaciers give fluvio-glacial deposits. These include :

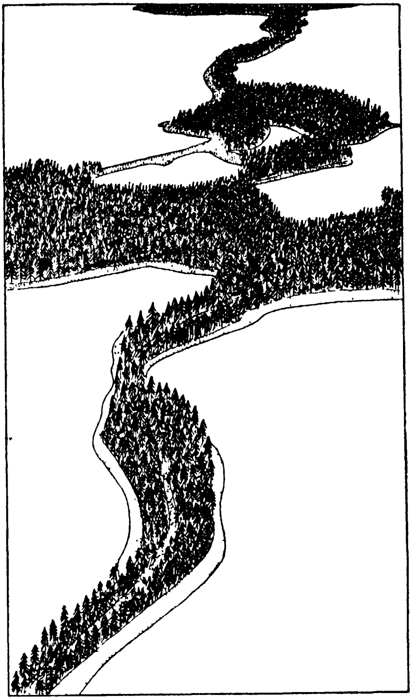


FIG. 96. A typical esker with transverse crevasse-filling, serving as a means of communication across a lake, Finland.

ESKERS or OSAR.—It has already been explained how the thaw-rivers of glaciers tend to flow in ice caves at the bottom. Such a subglacial river may choke its tunnel with gravel, which may remain when the ice melts to form a ridge, called an esker in this country and an os (plural osar) in Scandinavia (Fig. 96). Eskers can only be preserved if they form close to the melting edge of the glacier or in some part which has ceased to move; that is, has become what is known as dead ice. An os in Sweden is generally a succession of gravel mounds rather than a continuous gravel ridge. Each mound marks where a subglacial river dropped the coarser portion of its load near the mouth of its tunnel on entering standing water, which has since disappeared. The succession of mounds, formed in a succession of melting seasons, now looks like a string of giant beads, which has given rise to the descriptive phrase beaded os.

Kames are a network of gravel ridges, formed where rivers have discharged gravel into the crevasses of melting terminal ice (Fig. 97). They are in fact a specially irregular type of esker.

Gravel fans or spreads are laid down by braided rivers issuing on a land surface from glaciers, or may extend outwards for a considerable distance into shallow water.

Varves are extensive well-bedded deposits made of the finer material carried by glacial rivers and discharged into standing water. Great accumulations of such material formed in the Baltic at the end of the Glacial period. To-day the Baltic is greatly reduced in extent, so that we can examine its varves in many clay pits. Each thin bed is graded, starting suddenly with coarser material, supposed to mark the summer melting, and ending with very fine-grained material, supposed to represent the absence of melting during winter. Thus each bed is interpreted as having accumulated in a single year; and this theory, which is supported by collateral evidence, has been made the basis of a system of Pleistocene chronology.

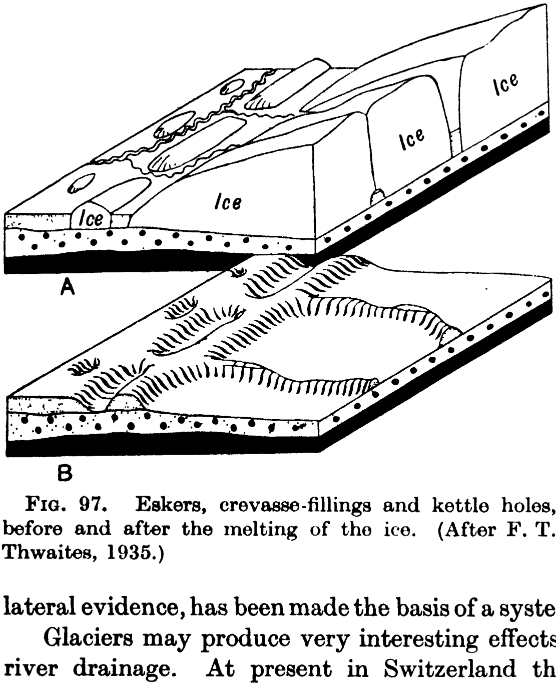


Fig. 97. Eskers, crevasse-fillings and kettle holes, before and after the melting of the ice. (After F. T. Thwaites, 1935.)

Glaciers may produce very interesting effects by temporary diversion of river drainage. At present in Switzerland there is one important lake dammed up in a tributary valley by a glacier coming down the main valley. In Britain there have been many such glacier-dammed lakes. The most famous is that of Glen Roy, where three beach lines mark successive levels of the lake, and form conspicuous objects on the hillsides known to every one as the Parallel Roads of Glen Roy (Figs. 98, 99). Each level of the lake corresponds to an outlet across some pass. The glaciers of the Ben Nevis range supplied the dam that impounded the Glen Roy lake. The position of the glaciers decided which of the three possible outlets should be used, and thus regulated the level of the lake's water.

In many cases where rivers have had their courses blocked by glaciers they have cut great gorges in ridges, across which they have been deflected. Later, when the glaciers have melted away, the gorges become deserted.

Dry valleys, or spillways, of this origin are very abundant in the East of Scotland, the North-East of Ireland, the Cleveland Hills, and elsewhere in England. One of the most important in the world is the valley by which canals, roads and railways approach Chicago from the south. It was cut by a river which drained Lake Michigan into the Mississipi basin, when a glacier prevented a northward escape. There were innumerable similar instances of glacial diversion of rivers in Canada at a time when the Canadian ice-sheet prevented rivers reaching Hudson Bay or the St. Lawrence. Enormous temporary lakes resulted, and the bottom deposits of one of the largest are responsible to-day for the wheat-fields of Winnipeg.

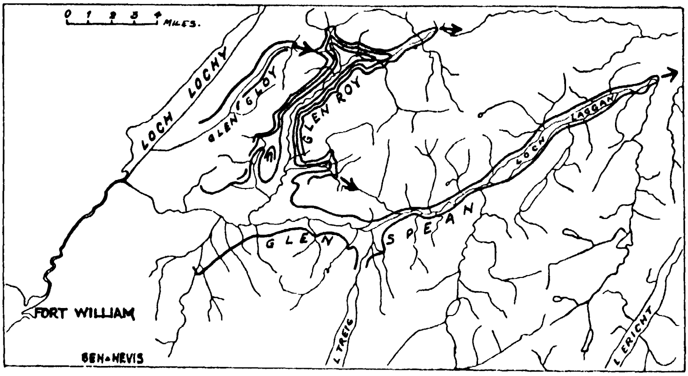


FIG. 98. Map of the Parallel Roads of Glen Roy.

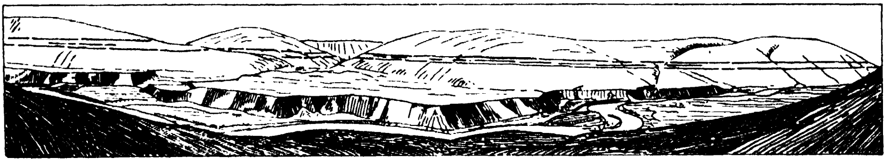


FIG. 99. View of the Parallel Roads of Glen Roy. (Geol. Surv. photo.)

Regions that have recently been glaciated often show signs of subsequent uplift. For instance, in Scotland and Norway we see raised beaches along the coast. The subject is difficult, but it is thought that glaciated lands, weighed down by thousands of feet of ice, slowly subside ; and then, when the ice melts, the land rises again according to the principle of isostasy.

CHAPTER XXXIX

LAKES

Lakes are interesting because the great majority cannot have resulted simply from river erosion. We have noted many origins, and here we may summarize the subject.

(1) Solution of limestone often gives hollows with underground drainage. If the exit of the hollow is blocked, a lake may result. Small examples are common in many limestone districts. Underground solution of salt has given rise to certain meres in Cheshire.

(2) Earth movement is responsible for many of the great lakes of the world, such as the Dead Sea, the lakes of the Great Rift Valley in Africa and the Great Salt Lake in America.

(3) Non-glacial deposits may dam up lagoons and lakes. Such deposits are gravel spits, blown sand, landslips and deltas. The deserted ox-bows of rivers like the Mississippi are blocked either end by river deposits.

(4) Glaciers often dam lakes with ice.

(5) Glacial deposits often supply dams, in the form of moraines, terminal or lateral, or of mere irregularities of boulder clay or gravel. There are a great many small examples of this type in Scotland. Linlithgow Loch is a kettle hole in gravel.

(6) Glacial erosion gives rock basins. Most big Scottish and English lakes serve as examples.

(7) Lakes of volcanic origin are either dammed by lava or occupy a crater. They are very common in volcanic districts. Lavas divert rivers and pond up lakes just in the same fashion as do glaciers.

CHAPTER XL

VOLCANOES

A VOLCANO used to be defined as a burning mountain. This definition is at present unpopular because most of the appearance of burning is deceptive. The apparent flames are mainly reflected glow from molten lava. The apparent smoke is dust produced by explosion, and clouds produced by condensation of steam.

In addition there are a number of very flat volcanoes, so that the word mountain is not always suitable. Some authors claim that the only feature present in all volcanoes is the channel up which molten material reaches the surface, and that therefore a volcano should be defined as a channel. This, however, leaves us in the difficult position of trying to explain that Vesuvius and Etna are not really volcanoes, but merely mountains built about volcanoes.

It seems preferable to keep closer to the old idea, and to define a volcano as an accumulation of material brought to the surface in a molten condition or by hot explosive gases.

We have already defined the terms lava, intrusion and volcanic ash.

Lava may flow at as much as a mile a minute, where very hot and on a steep slope ; but generally it only goes at a few miles an hour, and seldom kills people. When largely consolidated, lava crawls forward very slowly indeed.

Sometimes flow is maintained along particular courses that are crusted over. When the supply fails, the still liquid lava may pour out, leaving tunnels or caves. In some of our ancient lavas, especially those of Old Red Sandstone age, we find such caves filled up with sediment.

The surface of a lava may be comparatively smooth and billowy (Fig. 8), giving the pahoehoe type of Hawaii, often rucked up into narrow ridges described as ropy. The top material, though smooth at the surface, may be spongy inside.

Or the surface may be a broken mass of blocks, the aa type. This type is beautifully exhibited by many Scots lavas, where the spaces between are filled with sediment.

The fragmental material brought up by hot explosive gases, and called ash, is much more destructive than lava. After consolidation ash may be called tuff, especially the finer varieties ; the coarser consolidated types are generally spoken of as volcanic breccia or agglomerate.

The material of a volcanic ash may consist of non-volcanic stones, detached from the sides of the volcanic pipe ; or again of old consolidated lava broken up ; but much of it may originate in spurts and drops of liquid lava that consolidate in the air. If the spurts give fairly big stones these are called bombs, and if small stones, lapilli.

The most important gas in a volcanic eruption is steam, which may condense to rain. Ash saturated with rain-water frequently gives rise to disastrous mud-flows, the so-called mud lavas. They may flow downhill so fast as to be unescapable.

Central volcanoes are fed by pipes. Their typical form is a cone, with a central bowl-shaped hollow called a crater.

Fissure volcanoes are fed by fissures. Their typical form is a plain, with trifling cones along the line of fissure.

The shape of a volcanic cone is influenced by the nature of its material.

An ash cone typically steepens towards the crater, that is towards the source of supply.

A lava cone is typically dome-shaped, with a flattening of the summit determined by the outward flow of the lava. Acid and trachytic lavas are commonly very viscous, and a single flow may make a considerable steep-faced dome about a pipe. Basic lavas are much more fluid, and form very flat extensive domes, in which individual lavas are quite thin. Many cones, such as Vesuvius, are built of successive ashes and lavas. The rim of an ash crater tends to be built highest on the lee side as regards the prevalent wind. Accordingly lavas tend to escape in the opposite direction.

Some craters are very large, and are then called calderas. Calderas may result either from very violent explosions, called paroxysms, or from subsidence. Some authors try to limit the name caldera to a crater resulting from subsidence, which also is often called a sink ; but the origin of a great crater is frequently quite doubtful.

Volcanoes are certainly connected with the high temperatures which mining and boring show to exist in depth. On an average the temperature of the earth's crust rises 1° C. per 100 feet of descent. Pressure in depth tends to retard the melting of rock, but we are not going to consider this aspect further. Another effect of pressure, where it acts upon molten rock material or magma, is to keep gases like water vapour in solution. One of the main causes of volcanic eruption is the release of steam in magma, following release of pressure. The phenomenon is comparable with that obtained by uncorking ginger beer. A volcanic explosion is bigger and stronger, and it may hurl stones many miles up into the air. Steam of a volcano not only raises fragments, but may extrude lavas. Another analogy commonly cited is the boiling over of an ill-stirred porridge pot.

A second main cause of eruption is the squeezing of magma from the underground reservoir. This seems to be of particular importance where the outflow of lava is tranquil, as in the Hawaiian Islands.

Escapes of gas or vapour are common at volcanoes, and are called fumaroles. Among the gases emitted are HCl, H_2S, SO_2, H_2O and CO_2 ; also metallic chlorides and boric acid. The presence of metallic chlorides and boron compounds among volcanic emanations reminds us of many mineral veins. Where a volcano is nearly extinct, and the temperature near the surface has dropped, little of the gases emerge except CO_2.

Hot springs are also common in volcanic lands (Fig. 31). They are to a large extent supplied with water by rain, and with heat by subterranean magma. In Iceland, the Yellowstone Park and New Zealand some of the hot springs exhibit periodic eruptions and are known as geysers. Their behaviour is due to the heating of the lower part of a column of water. Boiling is delayed by the weight of the column until a temperature is reached considerably higher than that necessary to cause boiling at atmospheric pressure. When at last some of the top of the column is ejected or boiled away the pressure throughout is relieved, and much of the column flashes into steam, thus causing an eruption.

Volcanoes are restricted to certain regions of the earth's surface. The most striking feature of the distribution of active and recently extinct volcanoes is their tendency to occur along straight (Fig. 100) or arcuate lines.

FIG. 100. Chain of puys (small volcanoes) in the Auvergne, as seen from the summit of the Puy de Dôme.

These lines certainly mark the course of crustal fractures. The most important volcanic belt surrounds the Pacific Ocean, and forms the so-called Pacific Girdle of Fire. It runs along the west coast of the two Americas, crosses by the Aleutian Isles, skirts the east coast of Asia via Japan, and continues into New Zealand.

There are several volcanic lines in the Pacific, including the Hawaiian and Samoan islands.

Another well-marked line of volcanoes follows the Great Rift Valley of East Africa.

Other volcanic regions are less regular. The Italian volcanoes belong to the Mediterranean Zone. Many of the islands of the Atlantic, including Iceland and the Canaries, are volcanic.

ILLUSTRATIVE EXAMPLES.—Stromboli, one of the Lipari Islands north of Sicily, is always taken as furnishing the type example of constant eruption. Its activity is slight, but has been almost continuous through historic times. Stromboli is sometimes called the Lighthouse of the Mediterranean. It explodes every few minutes and occasionally pours out a little lava, but very seldom is dangerous.

Intermittent volcanoes are more common and more destructive. Their energy is bottled up, and then escapes with a rush. Vesuvius is typical. In early classical times it was apparently extinct, though at least one observer suspected its volcanic nature from its form. Gladiators on the occasion of a well-known and understandable strike used its crater as a fort. After a series of preparatory earthquakes a great eruption occurred in A.D. 79. It not only reopened the old crater but blew away a large part of the old wall. The rest of the wall remains as a collar on three sides of the modern cone and is called Monte Somma. Ash of the eruption buried Pompeii and a mud-flow buried Herculaneum. Admiral Pliny was killed, and his nephew has left an excellent account. Since then the volcano has been intermittently active with occasional long pauses.

Arthur's Seat in Edinburgh behaved in early Carboniferous times very much as Vesuvius in A.D. 79. There are two main necks exposed by erosion. The Lion's Head neck was half blown away by an explosion that gave rise to the Lion's Haunch neck (Fig. 101).

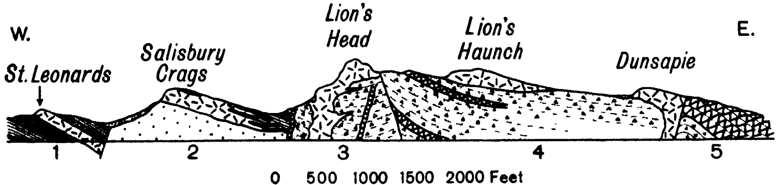


FIG. 101. Section across Arthur's Seat volcano, Edinburgh. (After B. N. Peach.)

1. Carboniferous sediments with St. Leonard's sill, faulted against
2. Old Red Sandstone covered by Salisbury Crags sill and Carboniferous sediments, broken through by
3. Lion's Head agglomerate neck with three intrusions, broken through by
4. Lion's Haunch agglomerate neck with Lion's Haunch and Dunsapie intrusions and two intra-crater lavas, truncating
5. Ashes covered by lavas of the cone.

A great explosion at a volcano, such as occurred at Vesuvius in A.D. 79, is called a paroxysm. The most famous paroxysmal eruption took place at Krakatoa, an island off Java, in 1883. Half of the island was blown away.

The noise was heard at a distance of 3,000 miles. A sea wave was raised that killed 3,600 people in neighbouring lands. Dust, blown 25 miles up into the air, was distributed over the whole world, causing brilliant sunsets even in our own country.

Another very famous paroxysm occurred in the West Indies in 1902, when on following days the Souffrière on St. Vincent, and Mt. Pelée on Martinique, gave rise to scorching clouds of ash, which rushed downhill and caused immense loss of life. Two interpretations have been offered of the scorching clouds: the first that they were jets directed by sideways explosion; the second that they rushed downhill in avalanche fashion propelled by their own weight. As in both localities they descended valleys, the second explanation seems the more likely. Another unusual feature of the Mt. Pelée eruption was the subsequent pushing up of a column of solid andesite from the throat of the volcano. The column rose slowly like a cork pushed gradually from a bottle, for 800 feet. It soon fell to pieces; but its fame remains, and it is known everywhere among geologists as Pelée's spine.

Approximate simultaneity of eruption, such as occurred at the Souffrière and Mt. Pelée, is unusual. As a rule neighbouring volcanoes, like Vesuvius and Etna, are quite independent in their times of eruption. In 1932, however, a number of Andean volcanoes burst into simultaneous eruption, though separated by great distances.

Vesuvius and Etna are not only independent in their times, but also in their materials. A Vesuvius lava is quite different mineralogically from an Etna lava. It is clear the two volcanoes have distinct reservoirs.

Parasitic cones are often built on the sides of a main cone. Two hundred such parasites exist at Etna. They are probably fed by intrusions of one or other of the types to be described presently as ring-dykes and cone-sheets; but this has not been decided.

The greatest central volcanoes of the world are in the Hawaiian Islands. Their material is basalt, and their form is flatly domed with calderas of subsidence, often termed sinks. The two best known occur on one island. One of them, Mauna Loa, reaches 14,000 feet above sea-level; the other, Kilauea, only attains 4,000 feet. Although just 20 miles apart, the two volcanoes are quite independent in their times of activity. Kilauea is the most studied volcano in the world. Its caldera is about 3 miles in diameter. Most of the floor is solid, but there is an almost persistent lake of liquid lava at one point. At intervals of 10 years or so, the lava of this lake is drained away by some lateral discharge on the flank of the volcano, and the solid floor of the caldera sinks rapidly, perhaps as much as 1,700 feet. Thereafter the lava lake refills, and the floor slowly mounts. All historic discharges have been by lateral fissures furnishing parasitic vents.

Perhaps the best modern example of a caldera of subsidence is afforded at Askja, Iceland's greatest volcano (Fig. 102). The caldera is of post-glacial date. It is 4½ miles in diameter, and is surrounded by rim craters, that is little craters due to emergence of lava around the rim of the sinking floor of the caldera. Askja as a whole is a basalt dome, but in 1875 a violent explosion perforated the floor of the caldera discharging rhyolitic ash, the dust of which fell as ' black snow ' in the Orkneys. A few months afterwards a minor sink, 1½ miles in diameter, developed within the old caldera alongside of the site of the explosion. It is now occupied by the Knebel Lake.

Askja with its rim volcanoes is particularly interesting to Scottish geologists because it is evidently the superficial counterpart of a Devonian cauldron subsidence that occurs at Glen Coe, encircled by a ring-dyke of granite (*cf.* Fig. 108 and Chapter LXV).

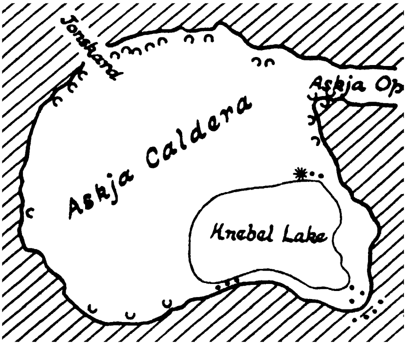


FIG. 102. Askja Caldera, Iceland.

Thick line = boundary cliff up to 1300 ft. high. Semicircles = rim volcanoes. Dots = fumeroles. Star north of Knebel Lake = site of 1875 eruption. Scale about 1 : 150,000.

Passing now from central to fissure eruptions we find that the Laki fissure in Iceland, in 1783, developed with a length of 20 miles, and erupted basalt, which spread as a plain for 30 miles on one side and 40 on the other. The eruption killed half the cattle of Iceland and led to a disastrous famine.

During Tertiary times there were numberless volcanic fissures in Scotland, now represented by north-west dykes of basalt. It is certain that some of these gave rise to fissure eruptions at the surface. Until recently it has been claimed that the Tertiary basalt lavas preserved in the Hebrides and Antrim were supplied by these fissures. Now many of us think that these particular lavas are of rather earlier date than the majority of the fissures, and that they issued from volcanoes of Hawaiian type, the sites of which are marked by plutonic intrusions in Mull, Skye and other centres.

The character of a fissure eruption depends partly upon the nature of the magma. Where this is fluid basalt, a plain is built up ; where the magma is acid and sticky, there may be only explosions. The best-known example of an acid fissure eruption occurred at Tarawera in New Zealand, 1886. It led to the destruction of a lake and of famous pink and white terraces built by hot springs of siliceous sinter.

The surface phenomena most usually observed at a volcano are explosion, outpouring of lava, fissuring and subsidence. At Usu San in Japan, 1910, an elevation occurred raising what is known as the New Mountain, complete with trees, 500 feet high in ten days. The elevation on one side was limited by a line of fault, with a row of explosion craters arranged along it.

Very many volcanoes are wholly submarine, and therefore out of sight. In other cases volcanoes, with craters above water, have been watched pouring lava into the sea. Such lava may continue to flow for miles under the sea, with its course marked by clouds of steam. The lava may build a tunnel for itself, and thus largely protect itself from direct contact with the water. Some basaltic lavas, where they meet water, have their surface congealed, in such a fashion that they advance by a process of budding. This was observed in 1905 at Matavanu, Samoa, where a lava continued flowing out of the crater for five years. The buds grow to the size of pillows and then may tumble off. Pillow-structure, each pillow with fine-grained chilled surface, is an indication of subaqueous flow. If there are vesicles they tend to be arranged in concentric zones (Fig. 103). Pillow lavas of Ordovician age and associated with marine sediments, are beautifully exposed at Ballantrae and Cader Idris. Other examples of Tertiary date occurring in Mull have helped us to trace the position of a crater lake, six miles in diameter.

FIG. 103. Pillow lava, Tayvallich peninsula, Argyll. (Geol. Surv. photo.)

CHAPTER XLI

IGNEOUS INTRUSIONS

WE can learn much more of the underground behaviour of magma by studying ancient eroded volcanoes, such as those of Scotland, than by visiting modern volcanoes, instructive though these be.

MINOR INTRUSIONS, often called hypabyssal, are of moderate thickness, though quite possibly of enormous lateral extent. They consolidate with medium or fine texture, and almost always have smooth compact chilled edges. Let us define a number of common forms, repeating what has already been said about the two commonest, dyke and sill.

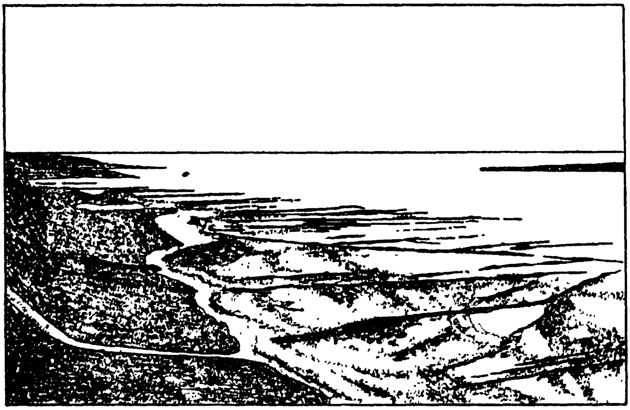


FIG. 104. South coast of Arran with Tertiary dykes of the Arran Swarm as reefs on the foreshore. (Geol. Surv. photo.)

A dyke is a vertical sheet of intrusive igneous rock, bounded by parallel sides. Individual dykes are generally not many feet in width. Where dykes of about the same age occur in great numbers they are said to constitute a dyke-swarm (Figs. 104, 105).

A sill is a sheet intruded at a low angle along bedding.

Sheets of other sorts seldom deserve special names ; sheet is quite good enough. In Mull and Skye, however, immense numbers of sheets incline steeply from all sides towards a common centre. Taken as a group such sheets have the form of a cone, with its apex pointing downwards. The individual sheets of such a complex are called cone-sheets.

A plug is a vertical intrusion with roughly circular cross-section, a vertical cylinder in fact. Many plugs are the fillings of volcanic necks, as Dumbarton Rock and Edinburgh Castle Rock.

The next two forms may sometimes be classed as minor, and sometimes as major, intrusions, according to their size.

Ring-dykes are much broader than ordinary dykes, and may often exceed a quarter of a mile in width. Their characteristic feature is their arcuate outcrop. They are shaped like gigantic serviette rings, partial or complete. Several ring-dykes, with different radii of curvature, are sometimes found grouped about a single centre, as in Mull.

A laccolith is a sheet with a flat undisturbed base and a domed upraised roof, so that the intrusion has a very considerable thickness in comparison with its lateral extent. The granite of northern Arran, a typical major intrusion, has domed its roof; but we do not know whether its base is undisturbed, so that we are not justified in calling it a laccolith.

MAJOR OR PLUTONIC INTRUSIONS are of great size in all three directions. Typically they are of coarse texture, and do not have chilled margins. If not classed as ring-dykes or laccoliths they are generally called stocks, bosses or batholiths, which are large intrusions with transgressive edges and with shapes that are often impossible to determine on the available evidence.

PROBLEMS

Now let us consider a few of the problems that arise in regard to intrusions.

DYKE-SWARMS.—A dyke is a tension phenomenon: the two sides have moved apart to allow the dyke to enter; the country is extended by the width of the dyke. This is clearly seen in two common phenomena:

(1) Where an irregularity occurs in one wall of a dyke, a corresponding irregularity occurs in the opposite wall, so that if the dyke were taken out the two walls would fit as in a jig-saw puzzle.

(2) Where a dyke cuts obliquely across dipping strata on flat ground, it displaces the outcrops by the amount of its own width.

The dykes of some dyke-swarms radiate from a focus. More often they are parallel to one another (Fig. 105). Thus a swarm of north-west south-east dykes can be traced in both directions from the Mull focus. The dykes get fewer and fewer as the focus is left behind; but Mull dykes are common in Ayrshire, and one of them even reaches into Yorkshire. The direction of such a parallel swarm of dykes can be accounted for by supposing that the dykes were successively intruded during the intermittent growth of a tension in the earth's crust, which tended to elongate the crust in a direction at right angles to that taken by the dykes. The problem still remains to account for a swarm passing through a particular relatively narrow focus, instead of its

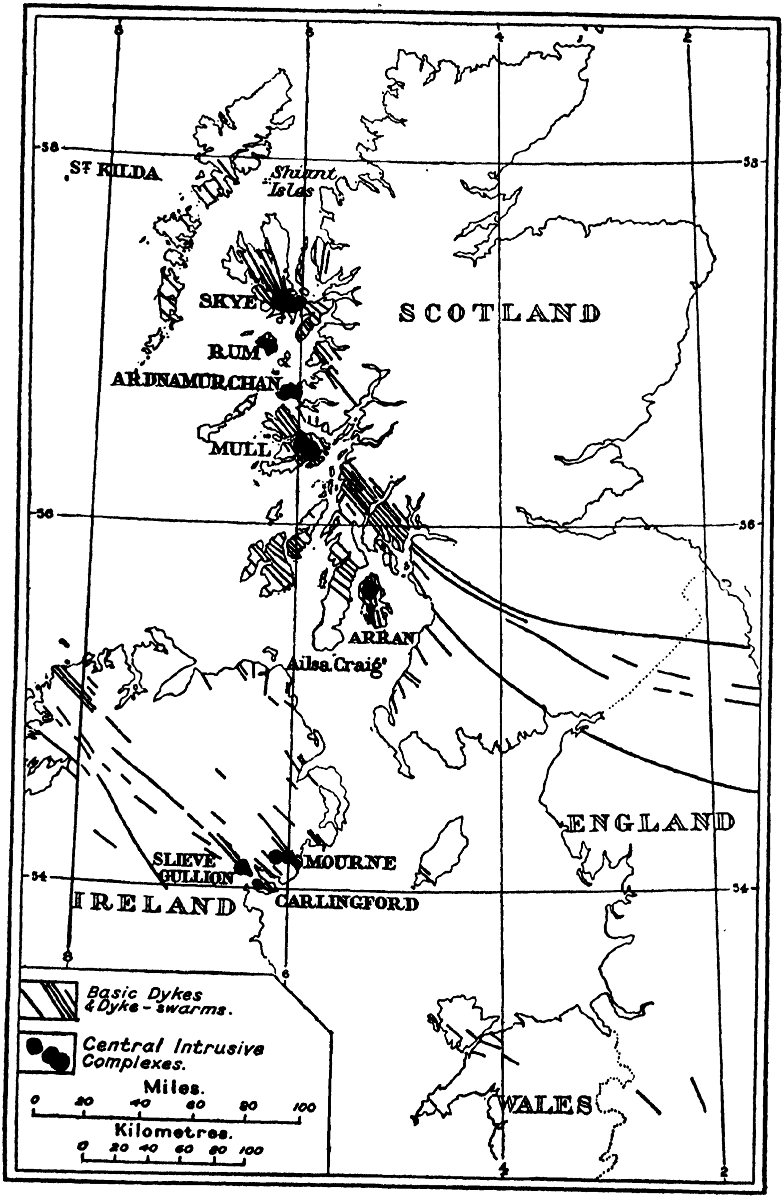


FIG. 105. Map of British Tertiary north-west dykes in relation to the plutonic centres of the time. (After Geol. Surv.)

In Nature the dykes are much more numerous than can be shown on a small-scale map.

component parallel dykes being distributed irregularly over a broad belt. The answer is that the earth's crust had already been perforated at the focus, so that, when the crust was pulled apart to give room for dykes, it tended to tear through the pre-existing hole. It is something like pulling a stamp out of a book of stamps : the paper tears at the perforations.

SILLS.—As sills approximately follow bedding, it is sometimes difficult to distinguish them from lavas. Let us consider a case where a sheet of igneous rock occurs with sediment above and below. Unless there is an important unconformity, anything that proves the igneous rock to be older than the overlying sediment proves it also to be a lava. Such evidence is provided by :

FIG. 106. Sandstone bedded in cavities in basalt lava of Lower Old Red Sandstone age, near Oban. (Geol. Surv. photo.)

(1) Pebbles of the igneous rock in the overlying sediment.

(2) Veins of sediment entering the igneous rock (Fig. 106).

(3) Absence of contact-alteration of the sediment.

(4) Marked vesicular top, which suggests that the igneous rock was not under pressure at the time of consolidation.

(5) Weathering of the top of the igneous rock, of such a nature as to indicate exposure before the overlying sediment was deposited. This is only found in subaerial lavas, and must be investigated critically, for intrusions often have decomposed tops. Weathering gives a residual, which, if deeply

buried, may develop a very characteristic flattened texture, with condensed ghosts of felspar recognisable with a lens.

(6) Pillow structure. This is only found in subaqueous lavas.

On the other hand, anything that proves that the igneous rock is younger than the overlying sediment proves it to be a sill. Thus :

(1) Fragments of the overlying sediment in the igneous rock.

(2) Veins of the igneous rock entering the sediment.

(3) Contact-alteration of the overlying sediment.

(4) Compact chilled even top (without pillow structure) of igneous rock against sediment.

(5) Transgression by igneous rock of bedding of overlying sediment.

(6) Disturbance of the overlying sediment.

Often also an inspection of the base of the igneous sheet gives valuable suggestions :

The base of a lava is usually vesicular or brecciated, follows the bedding accurately, and produces little or no contact-alteration.

The base of a sill is generally compact and chilled, and transgresses, veins and contact-alters the underlying sediment (Fig. 107).

FIG. 107. Dolerite intruded into Calciferous Sandstone, Hound Point, Firth of Forth. (Geol. Surv. photo.)

Also many sills are coarser than almost any lava. A sheet of basalt or fine dolerite may be either a lava or sill ; but one of coarse dolerite is almost certain to be a sill.

Sills are sometimes of wonderful extent. One of the best-known individuals is the Great Whin Sill of the North of England, a dolerite sill that outcrops in Northumberland. The Roman Wall takes advantage of its escarpment facing Scotland. What is probably the same sill comes down to earth in the Lanarkshire coalfield, and at Stirling furnishes the rock upon which the Castle stands, and at Queensferry provides foundations for the Forth Bridge.

Plutonic intrusions.—It is often very difficult to decide how great intrusive masses find room for themselves. The following methods have been advocated, and each of them may have operated in particular cases :

(1) Stoping, a word borrowed from the miner's vocabulary. In regard to intrusion, it means a sinking of country rock to make room for rising magma. Such stoping may be on a large scale, when a great mass sinks as a whole, or it may be piecemeal, as when isolated fragments sink. Stoping on a large scale may be described as a dropping down of the floor of an intrusion, leading to the development of a subterranean cauldron (Fig. 108).

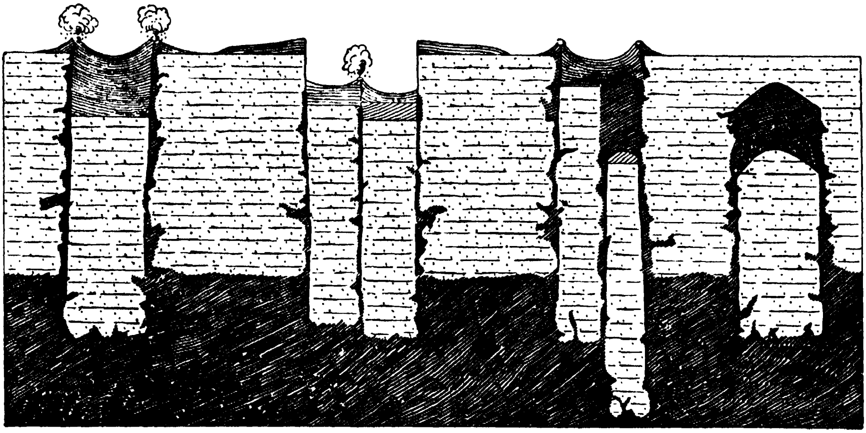


Fig. 108. Diagram illustrating subaerial and subterranean cauldron-subsidences accompanied by volcanic and plutonic accumulations of igneous rock. (After Geol. Surv.)

(2) Upheaval of the roof.

(3) Pushing aside the walls.

(4) Assimilation. To some extent a magma may dissolve country rock ; but as igneous rocks do not have the same composition as sedimentary rocks, no one can claim that an igneous intrusion results from mere melting of sediment *in situ*.

On the whole, stoping is probably the most important method of emplacement. One is justified in assuming that it has been employed wherever the local evidence shows that none of the other three methods has been adopted on more than a minor scale.

CHAPTER XLII

EARTHQUAKES

An earthquake is a shaking of the earth's surface.

The shake originates at some place on or under the earth's surface, and is transmitted to other parts by wave-deformation of the earth's crust.

A seaquake is a disturbance of the sea due to movement of the bed of the sea. A disastrous sea-wave is often developed, and commonly called a 'tidal wave'; but as it has nothing to do with tide it is better to employ for it the Japanese word tunami (or tsunami).

Earthquakes are of various origins, which may be classified under three main headings:

(1) Surface effects, such as landslips. The resultant earthquakes are trivial.

(2) Volcanic, due either to explosion or to earth-movements and fractures limited to the vicinity of a particular volcano. Such earthquakes are generally very local in their effects.

(3) Non-volcanic earth-movements. These are the main causes of great earthquakes.

The central area of a shaken district is called the epicentre of the earthquake. It is called epicentre, rather than centre or focus, because most earthquakes originate some considerable distance below the surface. The epicentre is the point or zone at the surface which is first shaken and most violently shaken. The fact that the disastrous effects of large earthquakes involve districts rather than countries shows that their underground focus is not very deep.

In practice an epicentre is located either by time records or by intensity records. A line which is shaken simultaneously is called a homoseist. By marking on a map the times at which an earthquake has been felt it is possible to draw a series of homoseists which will surround the epicentre. Each homoseist is a contour corresponding with some particular time of shake. Unfortunately earthquakes are propagated so rapidly that small mistakes in taking time records upset this method very badly. Accordingly the intensity method is much more often employed. A line which is shaken with the same intensity is called an isoseist. One of the main aims in the investigation of an earthquake is to draw a series of isoseists on the map of the district. It is necessary to have some scale for the measurement of intensity, and the scale must be based upon the experience of ordinary people subjected to the earthquake, for the recorder of the earthquake must get many of the data by advertising in the daily press.

The Rossi (Italian)-Forel (Geneva) Scale has been widely used. It recognises ten degrees of intensity according to the phenomena. The following is a very brief summary :

(1) Felt by very sensitive instruments.
(2) Felt by all instruments.
(3) Felt by people at rest.
(4) Felt by people in motion.
(5) Bells begin to ring.
(6) People awake.
(7) Church bells begin to ring.
(8) Chimneys begin to fall.
(9) Houses begin to fall.
(10) Total destruction.

The instruments mentioned under intensities (1) and (2) are seismographs designed to record earthquake tremors of very slight intensity. The principle of a seismograph is to arrange that some relatively heavy body shall be kept as nearly still as possible by its inertia, while the earth below is shaking. A pen attached to the stationary body will then scrawl a wiggle on paper attached to the moving earth. The paper is mounted on a revolving drum like that used with a self-recording barometer, and so the time of the earthquake is automatically recorded.

Seismographs differ in pattern. I shall describe one simple old-fashioned type designed to record shakes at right angles to its own plane. A steep mast carries a light boom, pivoted at the one end and suspended by a wire at the other. At this latter a heavy weight is fixed. If the earth is shaken by a vibration at right angles to the plane of the instrument the heavy bob tends to remain still owing to its inertia.

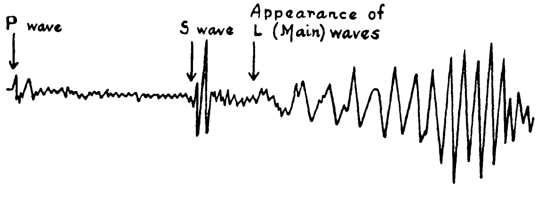


FIG. 109. Seismogram of 1909 earthquake registered at Pulkovo, Russia, with epicentre in Asia Minor, 2300 km. distant. (After Daly, after Gutenberg.)

Seismographs can be made so sensitive that they often detect earthquakes that originate on the other side of the earth.

The records received at a distance generally show three separate announcements of one and the same earthquake (Fig. 109) :

P : Preliminary tremors due to Push Waves.
S : Secondary tremors due to Shake Waves.
M or L : Main tremors due to Surface Waves.

The two first kinds go through the earth, and, partly because of this short cut, and partly because they travel quicker, they get ahead of the main or surface waves. The farther away an earthquake, the longer is the interval separating the time of arrival of the Preliminary and Main tremors. The distance of the earthquake from the seismograph can thus be calculated, and the fact that a disastrous earthquake has occurred in New Zealand may be known to observers in Britain before telegrams have arrived to confirm the fact.

The push waves are due to compression and expansion in the line of propagation of the wave. They can be transmitted both by solids and liquids and are able to traverse the entire body of the earth.

The shake waves are due to sideways distortion, in this respect like a wave sent along a rope. They travel more slowly than the push waves. Also they are of a kind that can only be transmitted by solids, and they seem unable to pass through the earth's centre. From this it is deduced that there is a considerable core of liquid matter at the earth's centre. From the high density of the earth as a whole this liquid core is thought to be molten iron. Uncombined iron is commonly found in nature as meteorites, so that it is quite probable that it also occurs at the earth's centre.

Earthquakes, though as a rule not directly connected with volcanoes, have a somewhat similar distribution (Fig. 110). The main earthquake belts are the *Circum-Pacific* and the *Mediterranean*, the latter reaching east through India to join hands with the Circum-Pacific.

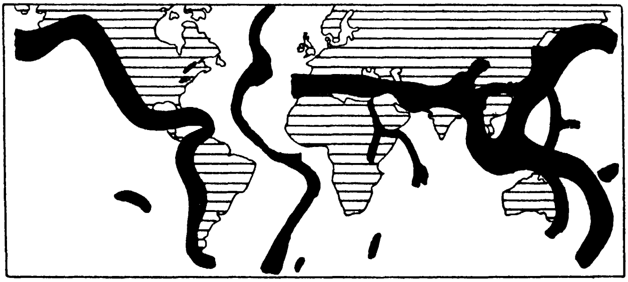


FIG. 110. The great earthquake belts of the world.

Some features of earthquakes are treated below in connection with particular examples.

The Lisbon earthquake of 1755 belongs to the Mediterranean belt. Like many other great earthquakes it was due to submarine faulting. Little damage was done to buildings founded on rock, but havoc resulted to parts of the town built on alluvium ; and great loss of life followed from a tunami. The Lisbon earthquake showed a most unusual capacity for agitating distant bodies of standing water. Loch Ness responded at 1,300 miles from the epicentre. Loch Lomond, not quite so far away, rose and fell with a 10-minute period for about an hour and a half.

The Alaska earthquake of 1899 was accompanied by the greatest uplift recorded on dry land in modern times, namely 47 feet. Like all earthquakes that affect hilly country it caused great landslips, and as many of these took the form of avalanches of snow from the mountains they led to a slow re-advance of a piedmont glacier (the Malaspina) that for many years had lain so stagnant that a forest had grown on its moraine-covered surface.

California and Japan have had a number of great earthquakes in comparatively recent years. They are remarkable for the clearness of the accompanying faulting. Some of the movement has been up or down, but in several cases the main movement has been sideways, shifting fences and roads, even as much as 21 feet, to right or left.

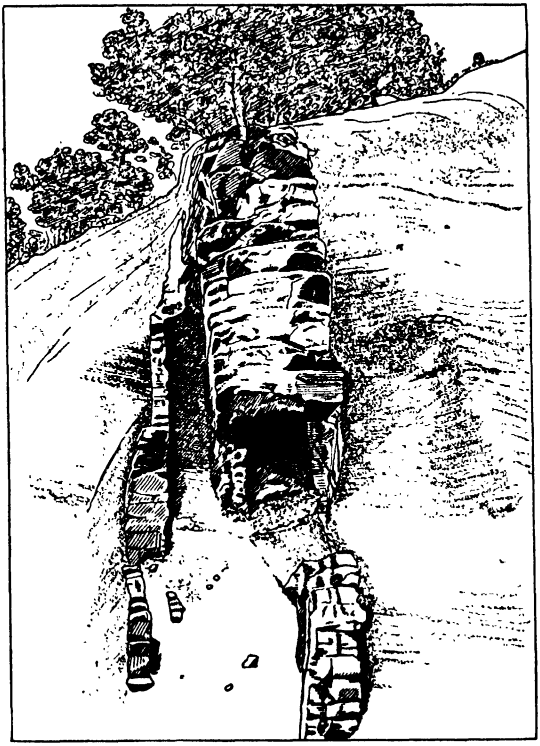


Fig. 111. Sandstone dyke, North California. (Diller, U.S. Geol. Surv., photo.)

Californian surveys show that previous to an earthquake the countryside slowly distorts, and then by a sudden snap, like the break of bending plank, it exchanges generalized distortion for localized fracture and displacement.

Japanese soundings in Sagami Bay, before and after the disastrous earthquake that led to the burning of Tokio in 1923, show great submarine movements with production of fault-scarps and submarine landslips.

Submarine faulting has in several other cases been recorded by breaks of a series of cables along some particular line at the time of an earthquake recorded on land by seismographs.

Britain must have had numberless severe earthquakes in its past as recorded by its important faults. Sometimes even now these old faults move again, and earthquakes of slight intensity have occurred at Inverness, due to a quiver along the Great Glen Fault, and at Comrie, due to movement of the Highland Border Fault. In fact, little harmless earthquakes are not really infrequent in the country as a whole.

Let us summarize some of the effects commonly accompanying earthquakes :

Landslips.

Fault-displacement.

Permanent flooding, or elevation, of coastal tracts.

Interference with surface drainage and production of lakes.

Fig. 112. Seismic boulder bed of Upper Jurassic date, Helmsdale, N.E. Scotland. (Geol. Surv. photo.)

Interference with underground drainage with destruction of old springs and opening of new.

Fissures that may be filled in with sediment (Fig. 111).

Mud volcanoes formed through the ejection of water-laden mud from porous unconsolidated material like alluvium. Sometimes hundreds of these so-called mud-volcanoes spring up on a shaken alluvial plain. Each volcano is only a few feet high.

Tunamis.

Fires in cities.

In the case of most old British earthquakes, faults supply the only conspicuous remaining evidence. The surface of the time has generally been removed by erosion. There is, however, a splendid record of earthquakes preserved in Upper Jurassic strata at Helmsdale on the east coast of Sutherland. The rock succession here is, in fact, a natural seismogram (Figs. 112, 113). Deposits were forming on the sea bed at the foot of a submarine fault-scarp. Every time fresh subsidence took place the accompanying earthquake shook off great landslips from the fault-scarp, some containing boulders up to 100 feet in length. A tunami raised by the earthquake spread out each landslip as a boulder bed, with big boulders below and rubble above. In periods of quiescence mud covered up the last-formed boulder bed, preparing a clean surface to receive the record of the next shock. It was like the rolling forward of fresh paper below the pen of a seismograph. Other records of the Helmsdale earthquakes are afforded by fissures filled with sand or rubble.

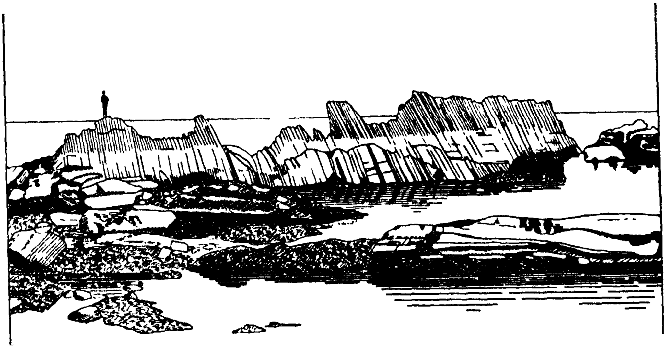


FIG. 113. Hundred-foot prostrate boulder of thin-bedded Old Red Sandstone in gently dipping Upper Jurassic seismic boulder bed. Strike of Jurassic seen behind water of immediate foreground. Helmsdale. (Geol. Surv. photo.)

The following rules are found of value in countries subject to earthquakes:

Beware of recent faults. Do not build towns on them, and, if it is necessary to cross one with an aqueduct, have a storage reservoir on the near side.

Beware of foundations of alluvium and surface deposits. In very many cases much more destruction has occurred in part of a town founded on alluvium than in neighbouring parts founded on solid rock. Venice provides an exception. It escapes earthquakes, probably because its alluvium is unusually deep.

Beware of low coasts and tapering bays. Tunamis are responsible for an appalling death-rate.

Note in which direction walls stood best in the last earthquake. Build your houses in this direction.

Where convenient use light bamboo houses, that rattle but don't break.

If heavy houses are necessary, dig their foundations deep. The displacements of the surface waves of earthquakes fall off rapidly in depth. If possible dig down to solid rock.

Use ferroconcrete or steel; they are strong and yet elastic. Bricks shake out separately.

Design to vibrate as a unit.

Avoid heavy-topped chimneys and arches and overhanging eaves, and minimize windows.

Build broad streets to escape danger from falling breakage and to prevent spread of fire. Tokio was wiped out by fire after the 1923 earthquake, and has been rebuilt accordingly. One can never read of this terrible disaster without a feeling of admiration for the courage with which Japanese meet misfortune.

Localize petrol risks and bursting reservoirs, and do anything possible to maintain water supply.

It is said that New York would survive a bad earthquake. Most of the city is built on rock. The skyscrapers are deeply founded, on piles where not on rock, and are constructed of steel and ferroconcrete. They are designed to face windstorms. Fortunately, too, earthquake shocks are not propagated to the tops of tall buildings. Still, though the skyscrapers might stand, their casing of stone or brick would fall. Heaven help the man in the street. As a matter of fact New York, like Britain, has a very good record, and is not likely to be dangerously shaken during the next few thousand years.

PART VI

PALAEONTOLOGY

CHAPTER XLIII

PROTOZOA AND PORIFERA

At this stage it seems desirable to return to the subject of fossils, already briefly introduced in Chapter V. Fossils are of fundamental importance to Geology, as indices alike of age and condition. In their study it should always be remembered that they are the remains of once living creatures. It is an honoured maxim in Geology that the Past is to be read in the light of the Present, and this is particularly true in the field of Palaeontology. A geologist working on fossiliferous strata must, to some extent, acquire a biological outlook, for he must seek to understand the principles which govern the classification of plants and animals alive to-day, and the subtle connections that subsist between form and function. The closeness of the relationship that links Geology and Biology is emphasized by the fact that the approach to Palaeontology is often made from the biological side with the special purpose of studying the records of evolution that have remained for millions of years in the keeping of the rocks.

Not all students of Geology can hope to find time and opportunity to add materially to the sum of human knowledge ; but every one should benefit from the exhilarating contacts which he is forced to make with kindred sciences. The following chapters provide a fuller and more biological treatment of Palaeontology than is common in an elementary work on Geology. The wealth of the material introduces a difficulty, for a beginner may find himself confronted with more than he can digest at a first reading. Perhaps the best plan is to begin by treating these palaeontological chapters as a picture book, to be enjoyed rather than memorized. When the student has obtained a general knowledge of the subject, and has passed on to the historical account that follows, he will soon discover a new need for understanding particular groups of organisms. Who can study the story of the Palaeozoic systems without wanting to know something intimate of trilobites and graptolites, brachiopods and corals? It is hoped that on turning back to the palaeontological descriptions the reader will find that they help to make the fossils live again. It is necessary that actual specimens should be handled, and highly desirable that they should be collected, even at an early stage of the course. Thus it may happen that some degree of specialization will be determined by the contents of the local rocks.

Fish caught the fancy of Hugh Miller when he lived at Cromarty on Old Red Sandstone, but if he had been brought up in the Isle of Wight he would probably have turned his attention to molluscs. Most of us are attracted to Vertebrate Palaeontology because we are vertebrates ourselves and so too are our domestic animals. On this account it is hoped that the chapters dealing with the vertebrates will be welcomed, although few universities include Vertebrate Palaeontology in a first year's course.

The complexity of biological classification becomes less alarming when we realise that even the uneducated appreciate many of the distinctions that are expressed in the terms adopted by scientists. For instance, the animal kingdom is divided into some ten phyla, and in the list that follows an attempt has been made to place familiar examples opposite each phylum in a parallel column. The fact that it is easy to give such examples for seven out of the ten phyla, combined with an instinctive recognition that profound differences separate the successive groups of examples, shows that the classification accords with common knowledge, although actually based upon independent and very critical investigation.

The reasons that in three cases familiar examples cannot be attached to particular phyla are worth considering. The Protozoa are extremely abundant, but are usually of microscopic size. The Bryozoa are larger, and are quite common as incrustations on the shells and seaweed of the seashore, but still they are definitely inconspicuous. The Brachiopoda, though big enough to attract attention, are relatively very rare. They are a phylum approaching extinction. This is a unique circumstance. Countless species and genera, and many families, orders and classes have come and gone in the world's history ; but the Brachiopoda alone seem to threaten the rule : once a phylum, always a phylum. As a curious result we may note that, while every geologist is familiar with the Brachiopoda of the rocks, very few have seen an example in the flesh.

Phylum	*Familiar Examples*
Protozoa	—
Porifera	Sponges
Coelentera	Sea-anemones, corals
Echinoderma	Star fish, sea urchins
Vermes	Worms
Arthropoda	Crustacea, insects, spiders
Bryozoa	—
Brachiopoda	—
Mollusca	Oysters, snails, octopuses
Chordata	Vertebrates, including fish, frogs, reptiles, mammals

There is a certain elasticity in the use of such terms as phylum, sub-kingdom, etc., and students must be prepared for differences of treatment in different text-books.

PROTOZOA

The Protozoa are very small, usually microscopic, animals that swarm in every wet or moist medium that can support life ; for example, they occur in the blood as germs of diseases like malaria and sleeping sickness. The body of a protozoon is a single cell, *i.e.* a corpuscle of protoplasm corresponding to one of the innumerable muscle, nerve, or bone cells that make up the tissues of the higher animals ; protoplasm is a jelly-like, transparent, living material of complex chemical constitution.

The Protozoa are typified by *Amoeba* (Fig. 114A), that lives in the greenish scum at the bottom of ponds, etc. Some *Amoeba* are parasitic ; they are mostly harmless, but one species gives rise in man to the dangerous amoebic dysentery. The body of *Amoeba* is a speck of protoplasm about 0·01 inch long, without any enduring shape. Near the centre is the nucleus which is denser and more finely granular than the surrounding protoplasm and has

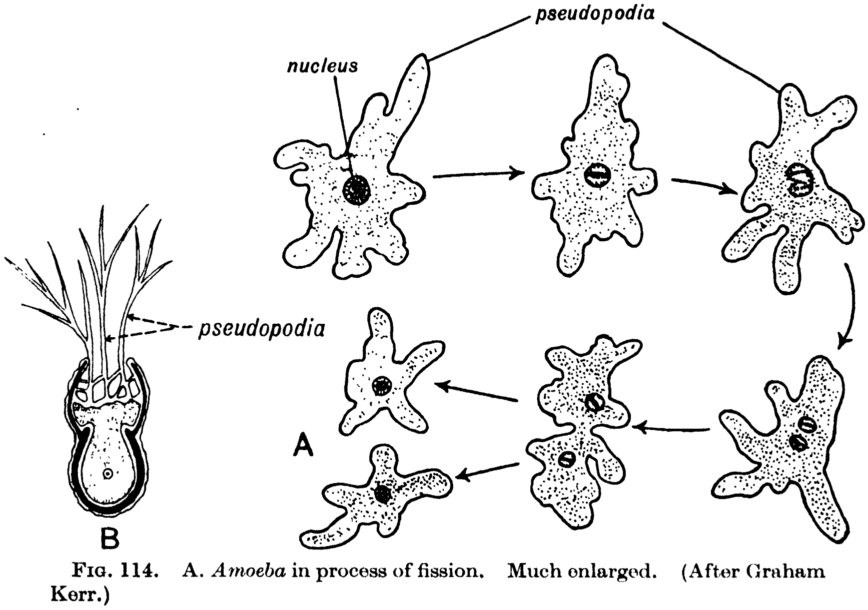


Fig. 114. A. *Amoeba* in process of fission. Much enlarged. (After Graham Kerr.)

B. Section of a foraminifer, showing test (black) enveloped in protoplasm, and pseudopodia emerging from the aperture. Contrast the branching and anastomosing pseudopodia with the lobate pseudopodia of Amoeba. (Modified after Twenhofel and Schrock.)

an important function in the reproductive processes of the cell. The animal moves by throwing out lobes or projections of protoplasm called pseudopodia —it projects some of the protoplasm of its body in the required direction, and follows with the rest of its protoplasm, which simply flows into the resulting pseudopodium. There are no organs—no heart, lungs, mouth, digestive or nervous systems. *Amoeba* feeds on microscopic specks of organic matter, which are taken in at any point on the surface of the body; the creature simply flows over and round the food particle, absorbing it and rejecting waste matter from any point on the surface of its body. All the functions—assimilation of food and oxygen, growth, reproduction—are performed by the single cell.

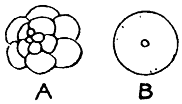


FIG. 115. Pelagic Foraminifera. Much enlarged. (After Murray.)

A. *Globigerina.*
B. *Orbulina.*

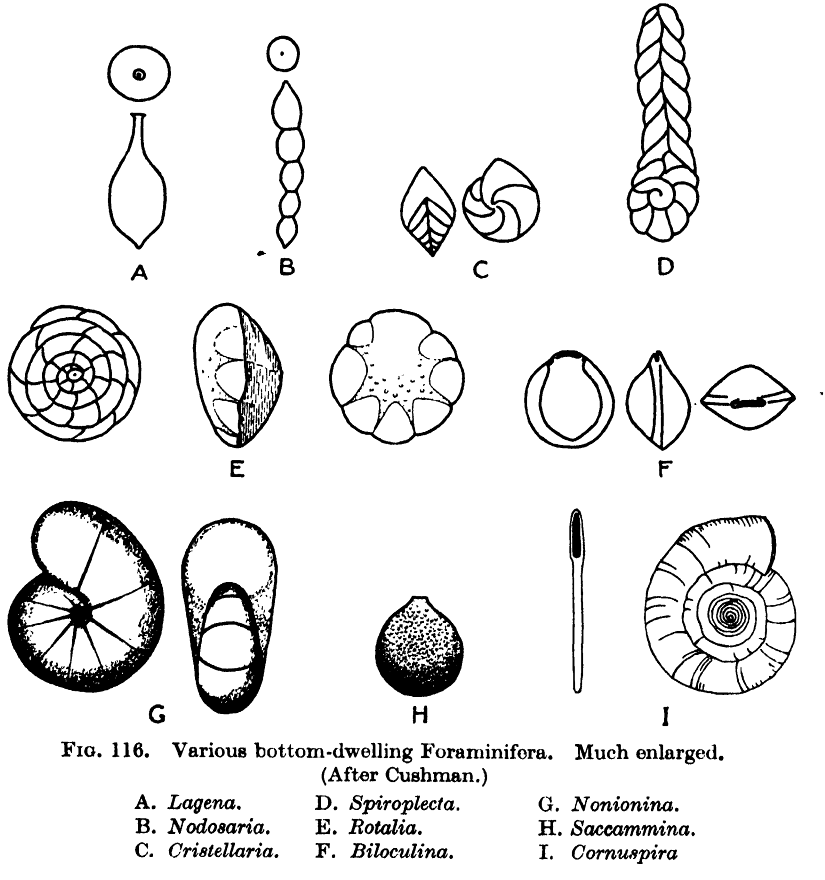


FIG. 116. Various bottom-dwelling Foraminifera. Much enlarged. (After Cushman.)

A. *Lagena.*
B. *Nodosaria.*
C. *Cristellaria.*
D. *Spiroplecta.*
E. *Rotalia.*
F. *Biloculina.*
G. *Nonionina.*
H. *Saccammina.*
I. *Cornuspira*

All the Protozoa do not change their shape like *Amoeba* by protruding and withdrawing pseudopodia. In most of them the external layer of protoplasm is comparatively rigid and gives a definite and enduring shape. Such forms propel themselves by lashing whips of protoplasm (flagella) or by vibrating hairs (cilia).

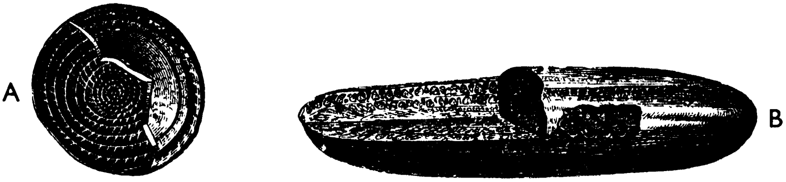


FIG. 117. Large foraminifera. (After Zittel.)
A. *Nummulites*. Discoidal test to show arrangement of chambers in whorls.
B. *Fusulina*. Fusiform test cut in three planes.

The Protozoa are elaborately classified. For our purposes only two orders need be remembered, Foraminifera and Radiolaria, both belonging to the class Rhizopoda (Protozoa with pseudopodia). These are the only Protozoa that secrete shells (tests), and therefore the only ones found fossil. Foraminiferan tests are internal (Fig. 114B) and in composition are chitinous, calcareous or formed of agglutinised sand-particles ; radiolarian tests are siliceous.

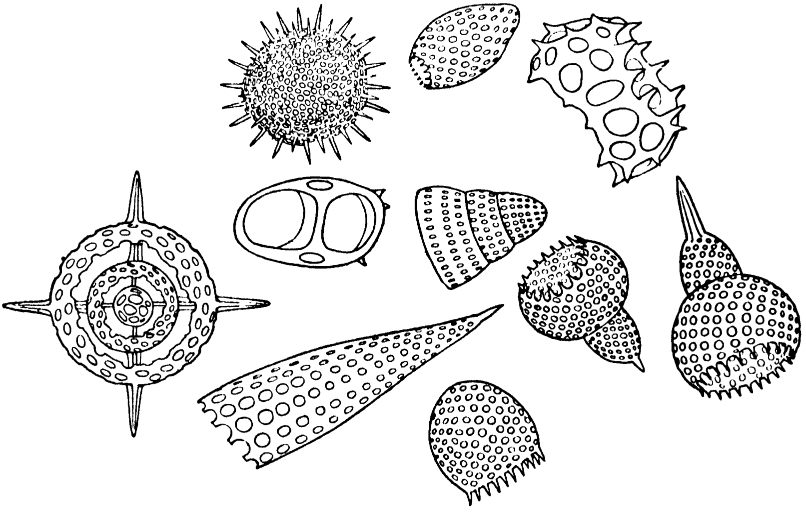


FIG. 118. Radiolaria. Much enlarged. (After Haeckel in Graham Kerr.)

The empty tests of pelagic Foraminifera (Fig. 115) sink to the ocean floor in enormous numbers, forming extensive deposits of foraminiferal ooze in the Organic Belt. Radiolarian ooze originates in the same way, and occurs at greater depths in the Organic Belt, because the siliceous tests of the Radiolaria resist solution under conditions that dissolve the calcareous tests of the Foraminifera (Chapter VIII).

The Radiolaria build elaborate lattice-work skeletons (Fig. 118). They occur in rocks of all ages from Precambrian to the present time, and their tests have formed cherts and flints and siliceous limestones at certain horizons. They are found in the Miocene of the Barbados, forming the 'Barbados Earth', and they make the so-called 'tripoli stone' (Miocene) of the Mediterranean region. On the whole they are not so useful for geological purposes as the Foraminifera, owing to the difficulties attending their detection and study.

The Foraminifera with their somewhat larger tests (Fig. 116), have proved of great importance, especially for the correlation of horizons in Cretaceous and Kainozoic rocks, commonly met with in boring for oil. They have chambered tests of varied shape and structure, and range from submicroscopic dimensions to the size of a penny in the discoidal *Nummulites* (Fig. 117A) of the Eocene.

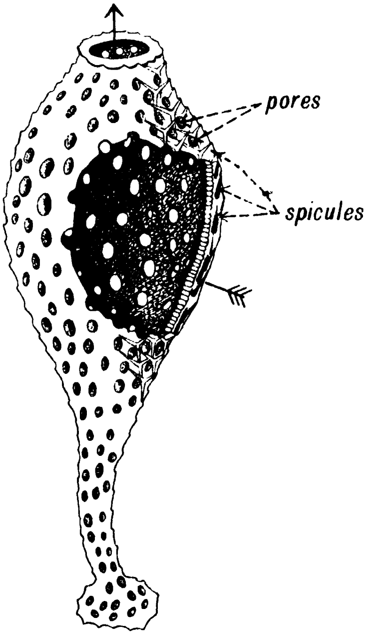


FIG. 119. Sponge. (Modified after Haeckel.)
Feathered arrow shows direction of water current from pores to osculum.

PORIFERA

The remaining animals are Metazoa; their bodies are composed of many cells, aggregated into organs for the performance of various functions.

The Porifera (sponges) are loosely organised communities of cells. There is a certain definiteness of external form that varies from species to species, but the shape of sponges is by no means stereotyped. Individuals vary so much that classification is extremely difficult. Sponges live in water, fixed to the bottom of the sea or pond. The common bath sponge lives round the shores of the Mediterranean, West Indies and Australia. The fibrous skeleton, with which we are familiar, is covered in life with flesh of the colour and consistency of liver.

The fleshy surface of a sponge has numerous small pores. A slow current of water is always passing through the body wall, entering at the pores, traversing a system of canals and chambers and discharging into the cloaca, a central sac-like or funnel-shaped cavity, the aperture of which is called the osculum (Fig. 119). This current is the only obvious sign of life—it brings food and ministers to the other physiological needs of the animal.

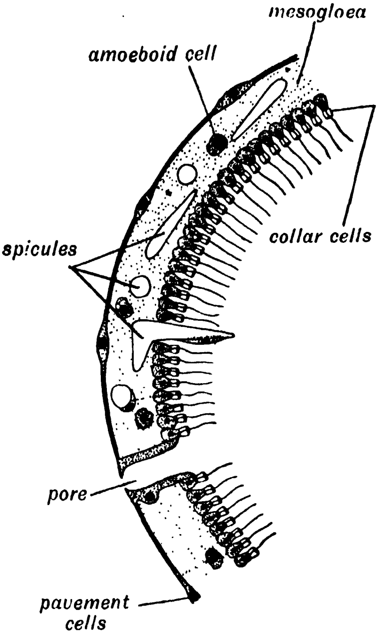


FIG. 120. Section of the body wall of a sponge. Much enlarged. (After Graham Kerr.)

The fleshy wall of a simple sponge (Fig. 120) carries on its inner surface flagellate collar cells and on its outer surface flat pavement cells. Between these two layers of cells is a slimy groundmass (mesogloea) in which are embedded the cells that secrete the skeleton, and amoeboid cells that transport food and excretory matter, or function as gonads. The collar cells resemble flagellate Protozoa, and cause a current of water in the sponge by lashing their long flagella. The transparent collars have the power of grasping organic particles suspended in the current and passing them down to the cells below, where they are digested. In more complicated sponges the flagellate collar cells are restricted to chambers which form part of a complex canal system traversing the body wall (Fig. 121). Sponges with a large or deep cloaca are considered as single individuals, those with numerous cloacae and oscula are regarded as colonies (Figs. 122, 123).

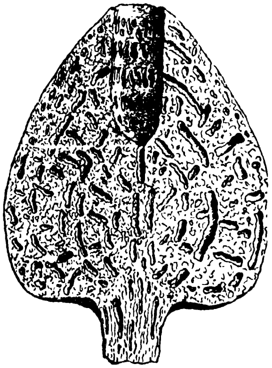


FIG. 121. Section of *Siphonia*, a thick-walled sponge of the Cretaceous with complicated system of canals, some radial and others parallel with the periphery. (After Sowerby.)

The sponge skeleton consists of units called spicules (Fig. 124), each the product of a single cell in the mesogloea. Spicules may be calcareous, or siliceous, or they may be composed of fibrous organic material called spongin ; the composition is characteristic of various large groups. Spicules may remain detached from each other in the mesogloea ; when the sponge dies and the flesh decays, such spicules fall to the sea floor, forming important constituents of ooze. On the other hand, spicules may be joined together to form a rigid frame-work that reproduces approximately the external form of the sponge. There are four main types of spicule, consisting of one, three, four or six rays coming off from a centre of growth—uniaxial (monaxon); triaxial; tetraxial (tetraxon); hexactinellid. These fundamental arrangements of the rays may be variously modified. Fibrous sponge skeletons are perishable and therefore all fossil sponges belong either to Silicispongiae of the orders Hexactinellida and Lithistida (siliceous sponges with irregular or nodular spicules of uniaxial or tetraxial plan) or to the Calcispongiae. The geological distribution of these groups is affected by the conditions in which they lived. The calcareous sponges have inhabited shallow coastal waters from Upper Paleozoic times, while the siliceous sponges have lived in deeper waters from Cambrian times until the present day. As fossils, sponges are most common in Britain in the Cretaceous.

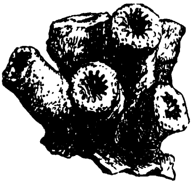


FIG. 122. *Eusiphonella*, a Cretaceous sponge, showing formation of a colony by budding. (After Zittel.)

FIG. 123. *Elasmostoma*, a Cretaceous sponge with numerous oscula. (After Zittel.)

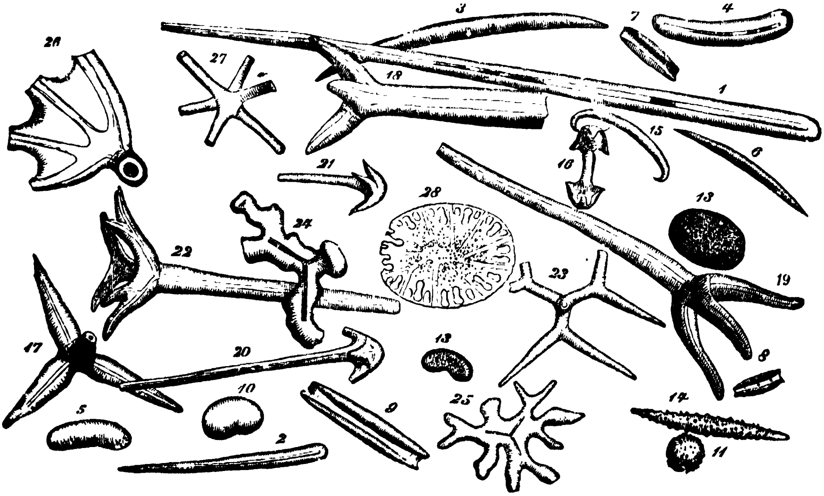


FIG. 124. Sponge spicules. Much enlarged. (After Zittel.)

CHAPTER XLIV

COELENTERA

THE coelenterates comprise such aquatic animals as jelly-fish, sea-anemones and corals. The small creature *Hydra* (Fig. 125) may be taken as representative. About a third of an inch long, it lives in fresh water. The body is like a small sac, with a mouth on the upper surface surrounded by tentacles. The body-wall consists of two layers of cells (Figs. 126, 127), outer and inner (ectoderm and endoderm), separated by a layer of mesogloea, usually feebly developed. There are stinging cells scattered over the surface and

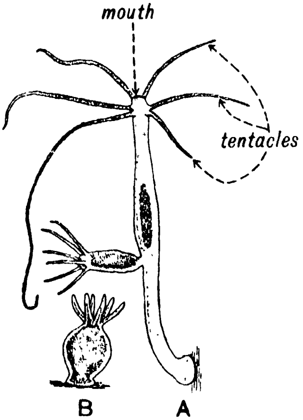


FIG. 125. *Hydra*. Enlarged. (After Shipley and MacBride.)

A. Expanded. Young individual budding off from parent.

B. Contracted.

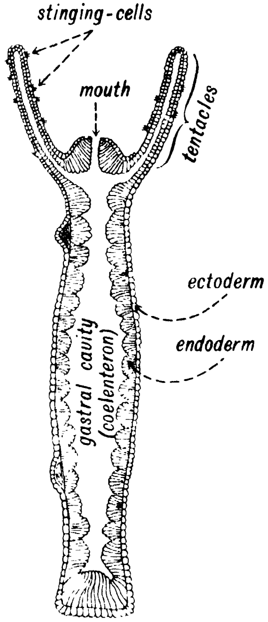


FIG. 126. Longitudinal section of *Hydra*. Much enlarged. (After Shipley and MacBride.)

particularly numerous on the tentacles (Fig. 126). These cells have a sensitive projection (cnidocil) which, when touched, releases from the cell a coiled thread, through which poison is ejected (Fig. 128). When the prey comes along, say a small crustacean, it is captured by the tentacles, paralyzed by the poison of the stinging cells, and then passed through the mouth to the gastral cavity, where the cells secrete a digestive juice that disintegrates the meal. The indigestible remains are voided through the mouth.

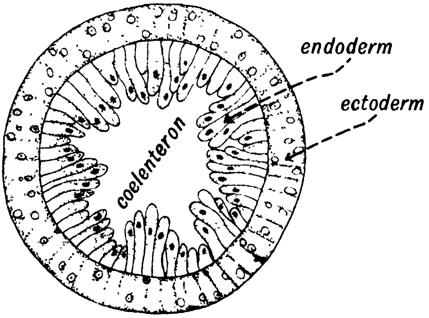


FIG. 127. Transverse section of *Hydra*. Much enlarged. (After Shipley and MacBride.)

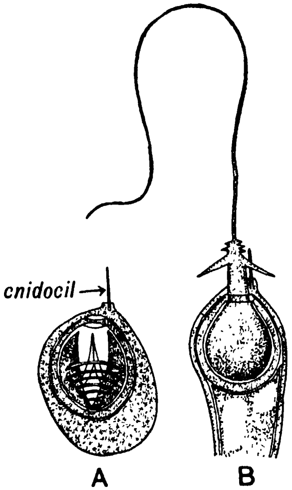


FIG. 128. Stinging thread-cell of *Hydra*. Much enlarged. (After Shipley and MacBride.)

A. Coiled. B. Discharged.

Coelenterates differ from sponges in having no canal system and no collar cells. In other respects they are more highly organised and have a definite shape based on radial symmetry, *i.e.* the body-wall is circular in transverse section.

The classes with fossil representatives are : Hydrozoa (Hydromedusae), Graptolithina, and Anthozoa.

The HYDROZOA are represented by *Hydra*, which has no hard parts and is not found fossil. It lives as a single polyp (a term applicable to any *Hydra*-like coelenterate individual), and reproduces sexually, or asexually by budding (Fig. 125A), the budded individuals ultimately detaching themselves from the parent. Many Hydrozoa, however, by budding produce polyps, which remain organically connected and secrete an external skeleton of chitin or calcium carbonate for the support of the colony.

The life history of *Obelia* may be taken as an example of the development of such a colony and also as an example of the phenomenon known as the alternation of generations. *Obelia* (Fig. 129) occurs as a light-brown, moss-like growth on sea-weed, rocks, etc., just below low-water. It consists of slender, branching threads of living substance, with *Hydra*-like polyps produced by budding. Branches and polyps are enclosed in a transparent horny sheath, which opens out into little cups (thecae) to receive the polyps. These cups are of two kinds : the first contain polyps like *Hydra,* with tentacles and stinging cells to catch food for the colony ; those of the second kind are in the form of a club-like cylinder (gonotheca) containing a fleshy rod covered with disc-like buds. These buds develop into tiny transparent 'jelly-fish' (medusae) about 0·1 inch across (Fig. 130). When properly developed they detach themselves and swim away, male and female. Hanging down under the bell are small bags filled with spermatozoa or eggs, which are shed into the sea where the sperms fertilise the eggs. A fertilised egg develops into a larva, which swims by means of cilia. The larva ultimately settles on to sea-weed or some other suitable object and develops into a colony similar to that with which we started. There are therefore two phases in the life history of *Obelia*—(1) a fixed colony of polyps that grows and

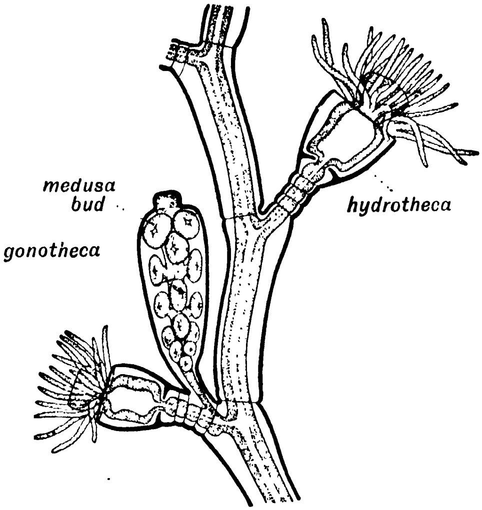


FIG. 129. *Obelia.* Portion of a colony showing two extended hydroid polyps and one gonotheca with medusoid buds. Enlarged. (After Maxwell in Graham Kerr.)

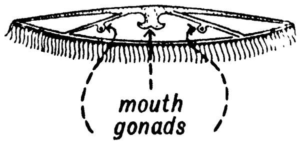


FIG. 130.—Medusa of *Obelia.* Enlarged. (After Fowler.)

produces new polyps by budding; (2) a free-swimming sexual medusa charged with founding new colonies in distant places.

Other coelenterates in their development are variations on the *Obelia* theme. The kind of life history that has been described, with its alternation between the free-swimming sexual medusa and the colony of budding polyps, underlies the whole coelenterate phylum, although it may be more or less profoundly modified. *Hydra*, the typical hydroid polyp, has no medusa phase in its development. It produces new polyps by budding, or sexually without the intervention of a medusa. Jelly-fish are simply large medusae that develop directly from the egg with only a transitory hydroid stage. *Obelia* carries its polyps on a branching stalk, and secretes a chitinous skeleton with thecae for the polyps. Its near relatives (Calyptoblastea) are rarely found fossil.

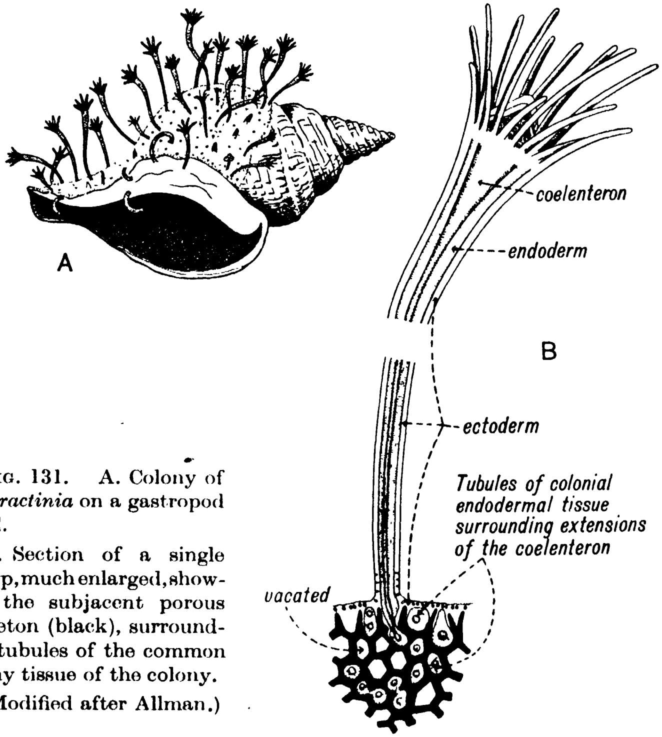


FIG. 131. A. Colony of *Hydractinia* on a gastropod shell.

B. Section of a single polyp, much enlarged, showing the subjacent porous skeleton (black), surrounding tubules of the common fleshy tissue of the colony.

(Modified after Allman.)

Other Hydrozoa, without hydrothecae, form moss-like growths on rocks and sea-weed near low-water mark and go through the alternation of generations shown by *Obelia*. A few are important as fossils. In *Hydractinia* (Fig. 131) the common fleshy tissue of the colony spreads over the surface to which the larva has fixed itself in a mass of endodermal tubules underlying a carpet of ectoderm. The tubules secrete a covering of chitin (rarely calcium carbonate). When the flesh decays on the death of the animal this skeletal material is left as a porous incrustation on the stone or shell. *Hydractinia* is commonly found encrusting shells of Kainozoic age.

In *Millepora* (Kainozoic) the skeleton is calcareous and contains tubes into which the polyps can withdraw when alarmed (Fig. 132B, C), but its relation to the common flesh of the colony is the same as in *Hydractinia*. The polyps are of two kinds, larger nutritive individuals with mouths, and smaller food-procuring polyps with tentacles but no mouth (Fig. 132A).

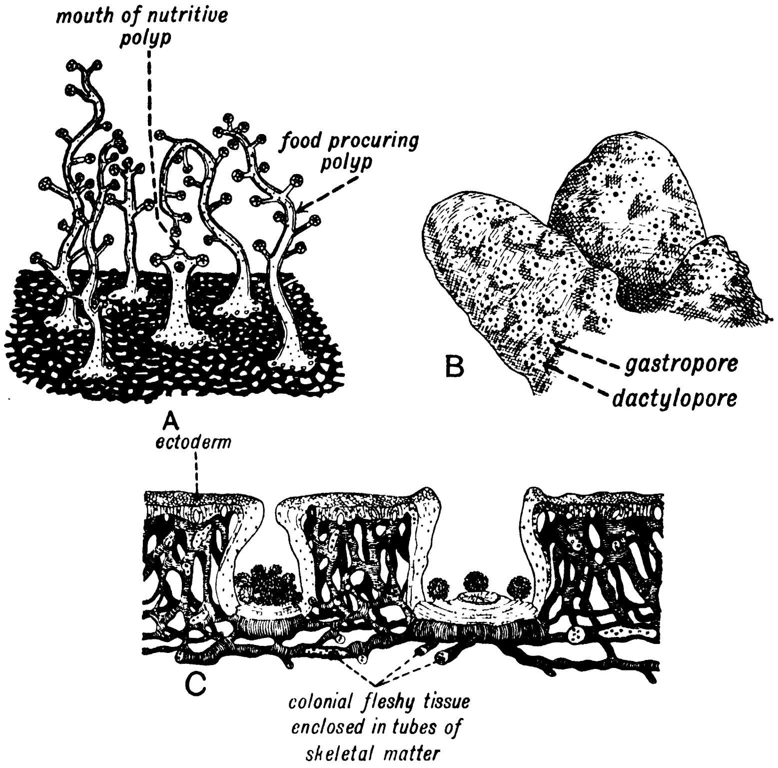


Fig. 132. *Millepora*. (Modified after Moseley.)

A. Part of a colony. A nutritive polyp (with mouth) is surrounded by five mouthless food-procuring polyps. Porous skeleton black.

B. Portion of skeleton, showing the large gastropores which house the nutritive polpys, each surrounded by ring of dactylopores which lodge the food-procuring polyps.

C. Section of part of a colony showing a nutritive and a food-procuring polyp withdrawn into their pores.

A and C much enlarged.

The tubes that accommodate the former are scattered like pores over the surface of the colonial skeleton, each surrounded by a ring of the smaller pores that accommodate the mouthless polyps (Fig. 132B).

The Stromatoporoidea were an order of predominantly Palaeozoic Hydrozoa which built up massive reefs, especially in the Devonian rocks (Fig. 298B). The colonial skeletons were composed of layers with a concentric structure connected by vertical pillars. The whole mass was permeated by minute canaliculi, and small tubes for the polyps were sparsely distributed. The relation of the colonial fleshy tissue to the skeleton was doubtless similar to that of *Millepora.*

The GRAPTOLITES (Figs. 283, 287, 288), extinct since the Palaeozoic, are of the greatest importance to the geologist. They were colonial organisms, enclosed like *Obelia* in a protective horny skeleton (rhabdosome) with thecae to receive the polyps. From the conical embryonic theca (called the sicula) one or more branches (stipes) grew out in various directions (Fig. 133). The branching skeleton of the colony, with its little thecae, has a general superficial resemblance to *Obelia*, and for a long time the graptolites were therefore regarded as Hydrozoa. On detailed comparison, however, the resemblance breaks down, and the graptolites are now placed in a separate class, the Graptolithina, of the phylum Coelentera. It is not even certain that they were coelenterates, and an old suggestion that they may be Bryozoa has recently been revived.

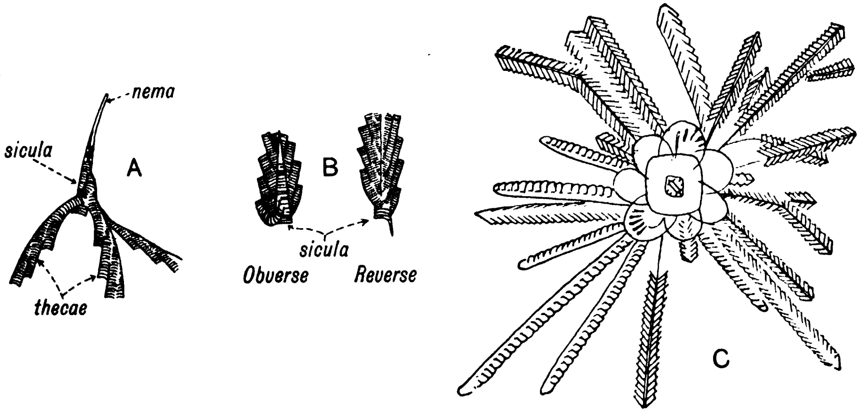


FIG. 133. Pendent, A, and scandent, B, graptolites showing proximal parts of the rhabdosome. Enlarged. (After Elles.) C. Synrhabdosome of *Diplograptus*. (After Ruedemann.)

Graptolite colonies floated near the surface of the sea, attached either to drifting sea-weed or to bell-like floats of their own. In the latter case they formed independent communities, known as synrhabdosomes (Fig. 133C).

Two orders are recognised—Dendroidea and Graptoloidea. The former are represented by *Dictyonema* (Figs. 135A and 383), a genus with thecae opening on the inner side of a pendent, conical rhabdosome, consisting of numerous slender stipes connected at intervals by transverse dissepiments. They had a long range in the Palaeozoic, and changed little. The latter are confined to the Tremadoc, Ordovician and Silurian rocks, and several circumstances combine to make them useful zone fossils—they evolved rapidly, their species were short-lived, their floating existence distributed them widely and quickly over the globe, and their remains occur in large numbers, especially in shale. Evolution in the graptolites took place along four main lines :

A. Reduction in the number of branches from many, in the Upper Cambrian (*Dictyonema*), to one, in *Azygograptus* and *Monograptus*, the latter dominant in the Silurian.

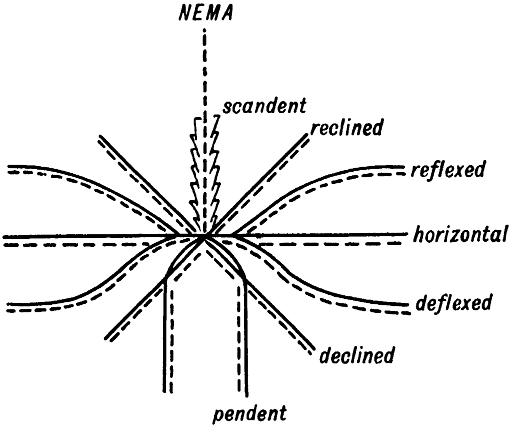


FIG. 134. Diagram to illustrate change in direction of growth of graptolites from pendent to scandent. Sicula at the origin with apex pointing upwards. (After Elles.)

B. Change in the direction of growth of the branches (Fig. 134) from the primitive position, in which they were pendent from the sicula (*Dictyonema*, etc.), through various intermediate positions to the scandent (*Diplograptus*, *Monograptus*) in which the thread-like attachment organ (nema) growing from the apex of the sicula, was effectively protected.

C. Change in shape of thecae from the primitive conical (Fig. 135A) and tubular (Fig. 133A), to sigmoid curvature of the outer (ventral) margin (Fig. 135B), that led in its extreme expression to introversion and introtortion of the apertural region (Fig. 135C). In some Monograptids the thecae became lobed (Fig. 135D), in others hooked (Fig. 135E), and in others isolated (Fig. 135F).

D. The fourth trend involved local thickenings of the skeletal substance, with the production of curious reticulate and spinose structures.

These four trends operated independently and at varying rates in different graptolite stocks. The resulting permutations and combinations of their evolutionary stages in successive graptolite faunas, have yielded a sensitive chronometer of the Ordovician and Silurian rocks.

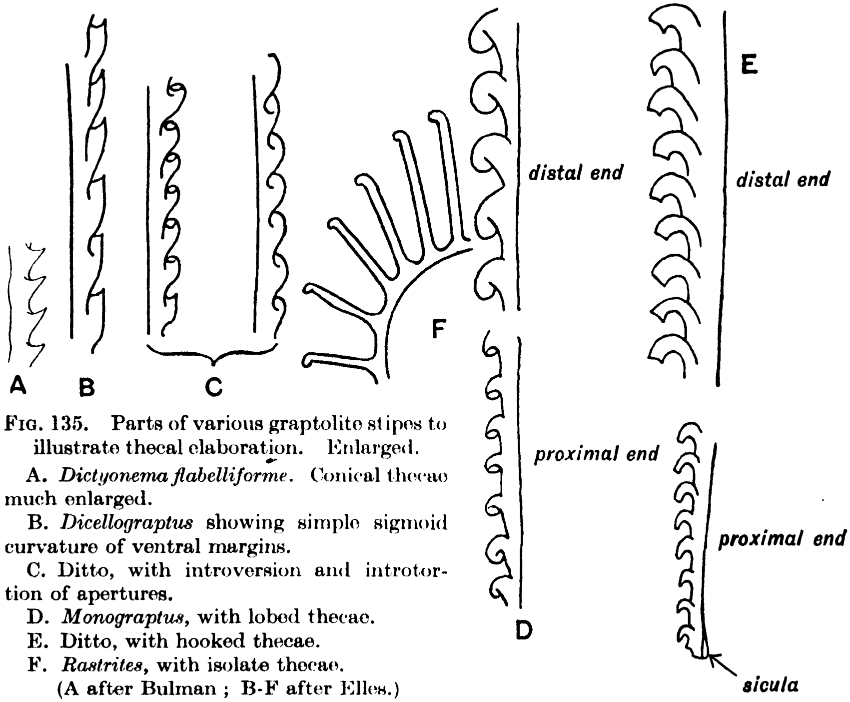


Fig. 135. Parts of various graptolite stipes to illustrate thecal elaboration. Enlarged.

A. *Dictyonema flabelliforme*. Conical thecae much enlarged.

B. *Dicellograptus* showing simple sigmoid curvature of ventral margins.

C. Ditto, with introversion and introtortion of apertures.

D. *Monograptus*, with lobed thecae.

E. Ditto, with hooked thecae.

F. *Rastrites*, with isolate thecae.

(A after Bulman ; B-F after Elles.)

The ANTHOZOA include the sea-anemones and most ' corals '. They exist only in the polyp phase, and no medusae are known. Some, like the sea-anemones of our coasts and certain corals, remain solitary throughout life, but in most cases, especially among the corals, there is extensive budding (or, it may be, fission) which results in the formation of colonies. Sea-anemones have no hard parts, but anthozoan corals build hard skeletons of calcium carbonate that fossilize well and, together with hydrozoan corals, calcareous algae and foraminiferan tests, often form massive reefs.

The gastral cavity of an anthozoon (Fig. 136) is divided into compartments by radial fleshy partitions (mesenteries), arranged in pairs and in one or more cycles. A short gullet hangs down from the mouth into the gastral cavity. Both mouth and gullet are laterally compressed, thus introducing a new element in animal form, bilateral symmetry, which, in the Anthozoa, is superposed on the dominant radial symmetry of the coelenterate.

The whole skeleton of a coral is the corallum ; in colonial corals individual skeletons of the compound corallum are called corallites. Compound corals may be freely branching (dendroid) with corallites of circular section (Fig. 304E) ; or with corallites in close contact throughout their length and of polygonal section (basaltiform, Figs. 288E, 304F) ; or with corallites set in a skeletal matrix (coenenchyma) secreted by the common fleshy tissue (coenosarc) of the colony (Fig. 298D). The skeleton may be secreted by the external surface of the body wall or within the body wall. The polyp rests in a depression (the calyx) at the top of the corallum or corallite. The wall of the corallum is the theca, and the epitheca is a calcareous layer outside the theca, secreted by the edge zone. As the polyp grows, its base is raised to higher levels in the corallum, and secretes within the theca a number of structural elements that are known collectively as endotheca. The radial plates of the endotheca are known as septa; they are secreted within infoldings of the base of the polyp, each radial invagination corresponding to the space between a pair of mesenteries of a given cycle.

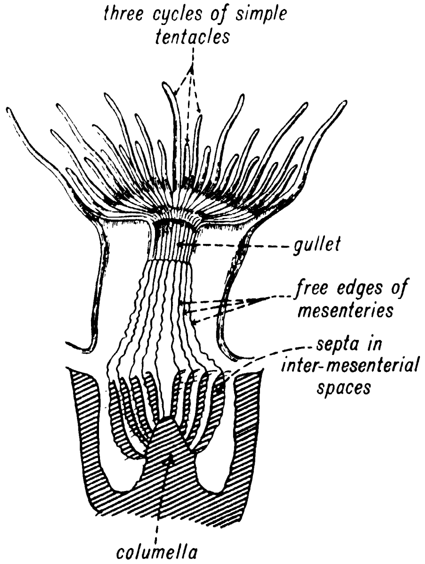


FIG. 136. Section of a coral polyp, showing its relations to the skeleton (heavy oblique shading). (Modified after Claus, after Lacaze-Duthiers.)

Corals are useful fossils from the Lower Palaeozoic onward. Along with certain brachiopods, corals of the extinct Palaeozoic order Tetracoralla are used to zone the rocks of the Carboniferous Limestone Series. The Tetracoralla (sometimes called rugose corals, from their characteristically wrinkled epitheca) were simple or compound corals (Fig. 304), showing a fourfold plan in their septal development that clearly involves bilateral symmetry. Their place was taken in Mesozoic and later times by the Madreporaria, simple or compound corals which are united with sea-anemones to form the order Hexacoralla, with simple tentacles and with mesenteries (and septa in the corals) arranged in multiples of six. The Alcyonarian corals with eight plumose tentacles and eight mesenteries constitute the order Octocoralla, and range from Lower Palaeozoic to the present. A skeleton is usually developed, varying in character from detached calcareous bodies in the body wall to massive basal coralla like those of *Heliopora*. In *Heliopora* two kinds of tube-like corallites occur in the coenenchyma—one series (the autopores) contains the normal polyps, and a series of smaller tubes (siphonopores) contains caeca suspended from the under surface of the coenosarc (Fig. 137). *Heliolites* (Fig. 298D), a characteristic coral of the Lower Palaeozoic, was analogous in structure to *Heliopora*. In both genera septa are short, but tabulae (horizontal plates) are strongly developed in the autopores and siphonopores. Corallites with tabulae, but with septa rudimentary or absent, also characterized other genera of the extinct Palaeozoic group of the Tabulata, in which composite coralla of various forms were produced each by its characteristic type of budding. Thus in *Halysites* (Fig. 288F), the chain coral (Ordovician and especially Silurian), budding occurred periodically on one side, producing linear series of adjacent corallites, whereas in *Favosites* (Fig. 288E), common in Silurian and Devonian, budding took place frequently on all sides, producing compact coralla with prismatic corallites and mural pores that probably represented the tubes connecting the parallel cylindrical corallites of the related genus *Syringopora*.

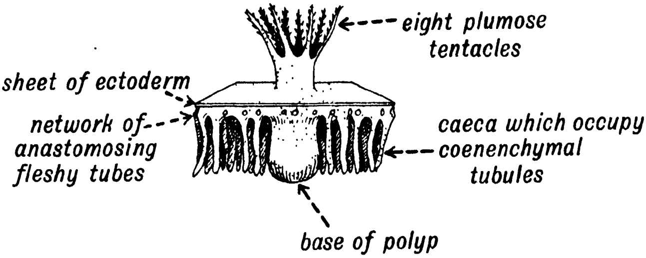


FIG. 137.—Portion of Alcyonarian colony with one polyp. Skeleton has been removed to show base of polyp and caeca. Enlarged. (After Bourne.)

CHAPTER XLV

ECHINODERMA

THE Echinoderma and remaining phyla develop an alimentary tract surrounded by a body-cavity, or coelome (Fig. 138C), and hence may be grouped as Coelomata, in contrast to Coelentera, just described, which have only a simple gastral pouch, or coelenteron (Fig. 138A). The first stage in the evolution of the coelome and alimentary tract is the development of mesoderm, a packing of cells between ectoderm and endoderm (Fig. 138B). The body-cavity is simply an opening in this mesoderm, containing heart, lungs, liver, etc., which are therefore of mesodermal origin.

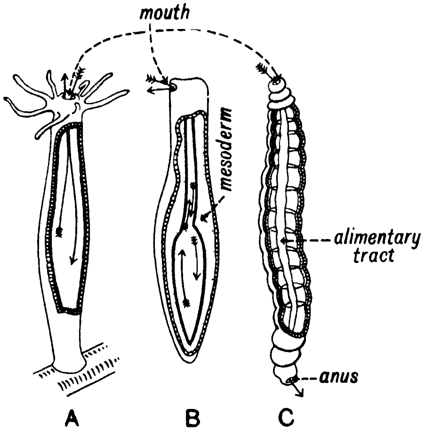


FIG. 138. Diagrammatic sections of a coelenterate (A), a flat-worm (B), and an annelid worm (C), to illustrate the nature of the body cavity, alimentary tract and segmentation. Not to scale. (Modified after Wells, Huxley and Wells.)

The Echinoderma include star-fish, sea-urchins, sea-lilies, and kindred creatures, characterized by five-rayed symmetry. The STAR-FISH (Fig. 139) consists of five so-called arms radiating from a central disc. The arms are hollow, and contain branches of the intestine and other viscera. The mouth lies in the centre of the under surface, and the anus on the upper surface of the disc. Five broad grooves (ambulacra) radiate from the mouth, one along the under surface of each arm. Each ambulacrum is furnished with a double or quadruple row of little tubes that end in suckers. These are the tube-feet (podia) ; and by their aid the animal moves and grasps its prey. Within the body there is a system of pipes and reservoirs containing watery fluid. This water-vascular system opens to the exterior through a porous plate, the madreporite, situated near the anus. The star-fish extends its tube-feet for action by forcing liquid into them from the water vascular system, and withdraws them from use by allowing the water to flow back again into the system. The water-vascular system consists of a calcareous tube leading from the madreporite to a tubular vessel encircling the gullet, and five radial tubes leading off from the circular vessel, one down each arm. The radial vessels give off in pairs, one on either side, numerous short branches, each carrying a little bulb or ampulla. The ampullae act as reservoirs, controlling individual tube-feet. The tube-feet are closely crowded, and their collective strength is considerable. Some of the larger star-fish can tear open oyster shells, and often do serious damage to oyster beds. The ambulacra are roofed with calcareous plates, between which are the pores that allow the tube-feet to connect with the ampullae within the test. The water-vascular system and ambulacral areas are unique and characteristic features of echinoderms.

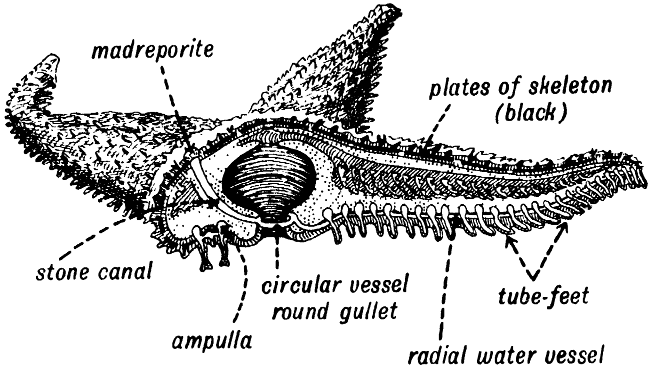


FIG. 139. Section of a star-fish passing through one radius (arm) and the opposite inter-radius. (Modified after Schmeil.)

Calcareous plates developed in the mesoderm form a rigid support for the body. It is this platy skeleton that fossilises.

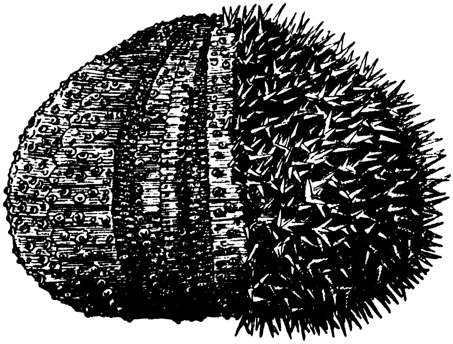


FIG. 140. An echinoid with spines removed from one half of the test. Spines are usually detached in fossil echinoids.

The SEA-URCHINS (ECHINOIDEA) are the most important echinoderms for geological purposes. They occur sporadically in Palaeozoic rocks and are useful time indices both in Mesozoic and Kainozoic. The genus *Micraster* (Fig. 318) affords an interesting and chronologically valuable record of continuous evolution in the Upper Chalk.

The spiny tests of sea-urchins are globular, discoidal or heart-shaped (Figs. 140, 318), and the radii do not project to form arms, as in the star-fish. The plated skeleton consists of two main regions, corona and apical disc. In the adults of most echinoids the corona forms the bulk of the test. In Mesozoic and Kainozoic echinoids it is typically composed of twenty columns of plates, which make up five ambulacra (radii) alternating with five interambulacra (interradii), each composed of two columns of plates. The ambulacral plates are small, each plate pierced by a pair of pores. The radial canals of the water-vascular system pass beneath the ambulacra, and podia (tube-feet) are protruded through the pores. The interambulacral plates are large and have no pores, but bear spines attached to tubercles; usually the spines are detached in the fossil. The ambulacra may also bear spines. Palaeozoic echinoids may have from 2–20 columns of plates in each ambulacral area and from 1–14 in each interambulacrum.

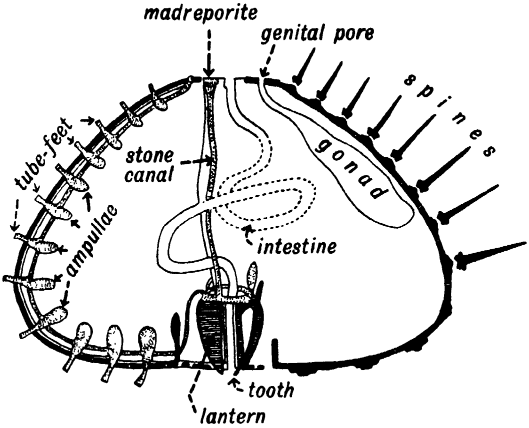


Fig. 141. Diagrammatic section of an echinoid. (Modified after Gregory.)

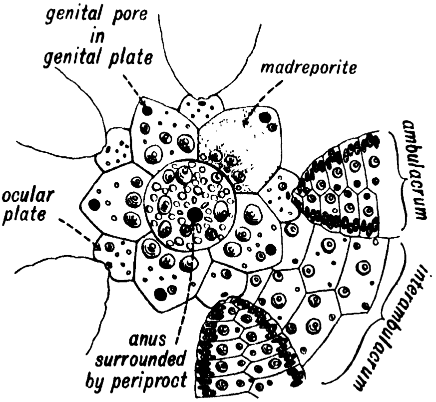


Fig. 142. Apical system of *Echinus*, a Recent 'regular' echinoid.

The apical disc (Fig. 142) is situated at the aboral pole of the test and usually consists of ten plates—five ocular plates situated radially and alternating with five interradial genital plates. Ocular plates have typically a single pore related to a large primitive tentacle and not to a visual organ. The genital plates have one or more pores (Figs. 141, 142), for extruding the products of the sex organs which lie below the interambulacra; one genital plate (the right anterior) has numerous madreporic pores that communicate with the water-vascular system. In the regular, pentamerally symmetrical echinoids, the anus and its surrounding plated membrane, the periproct, lie within the apical disc.

An important feature in the evolution of one group of echinoids is the development of bilateral symmetry, superposed on the characteristic pentameral symmetry of the phylum. Pentameral symmetry is a special case of radial symmetry, which animals tend to develop when they spend their post-larval life attached to the sea-floor. In the case of the free-moving star-fish and echinoids the radial symmetry must be regarded as a relic of a 'fixed' ancestry, and we shall see that the earliest echinoderms of which we have fossils were attached forms. Free-moving, radially symmetrical animals can move horizontally in all directions with equal facility ; in the case of the star-fish, any of the arms may act as a temporary head, giving direction to the movement. Such a creature is hardly a speed-model. For rapid directed movement in animals, bilateral symmetry of structure is necessary. In the 'irregular' echinoids we see the rudiments of this bilateral symmetry as expressed in free-moving coelomate animals, and its highest expression is found in the stream-lined body of the fish. This does not imply any ancestral connection between irregular echinoids and fish ; there is no such connection. Bilateral symmetry has been independently evolved by the major groups of coelomate animals. The irregular echinoids and many other bilaterally symmetrical animals are not speedy, but they possess the fundamental symmetry of structure from which speedy forms have in other cases been derived.

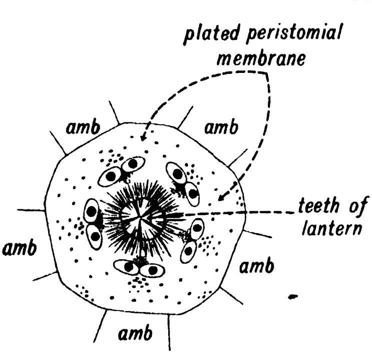


FIG. 143. Peristome of *Echinus*. amb, ambulacrum.

In echinoids bilateral symmetry is achieved by the backward movement of the anus from the centre of the upper surface, until ultimately it reaches the edge of the test. In some of these irregular forms the mouth and its surrounding plated membrane (peristome) remain in the centre of the under surface (Fig. 143) ; in others they move forward to the edge of the test, giving the highest expression of bilateral symmetry, mouth in front, anus in rear, as in *Micraster* (Fig. 318). Such forms feed like worms, by scooping up mud and passing it through the alimentary tract, where the nutriment is extracted. The 'regular' forms, on the other hand, browse over sea-weed, cutting it into small pieces by means of five teeth worked by an arrangement of muscles and plates and called Aristotle's Lantern (Figs. 141, 143). Bilateral symmetry is developed also in the group of echinoderms that includes the sausage-shaped sea-cucumber and bèche-de-mer, but these are not found fossil.

Star-fish and sea-urchins belong to the class of free-moving echinoderms (Eleutherozoa). Other forms live more or less permanently fixed to the sea-floor (Pelmatozoa). Such are the fossil and modern sea-lilies (Crinoidea) and the extinct Cystoidea, Blastoidea and Edrioasteroidea.

The typical CRINOID (Fig. 144) is borne on a long flexible stalk of superposed cylindrical or pentagonal plates (columnals), pierced for the passage of nerves and blood vessels. Stalks with a length of 20 metres have been recorded. The principal organs are contained in a globular, cup-, or bowl-shaped capsule called the calyx. The lower or dorsal part of the calyx, connected with the stalk, is composed fundamentally of two or three rings of

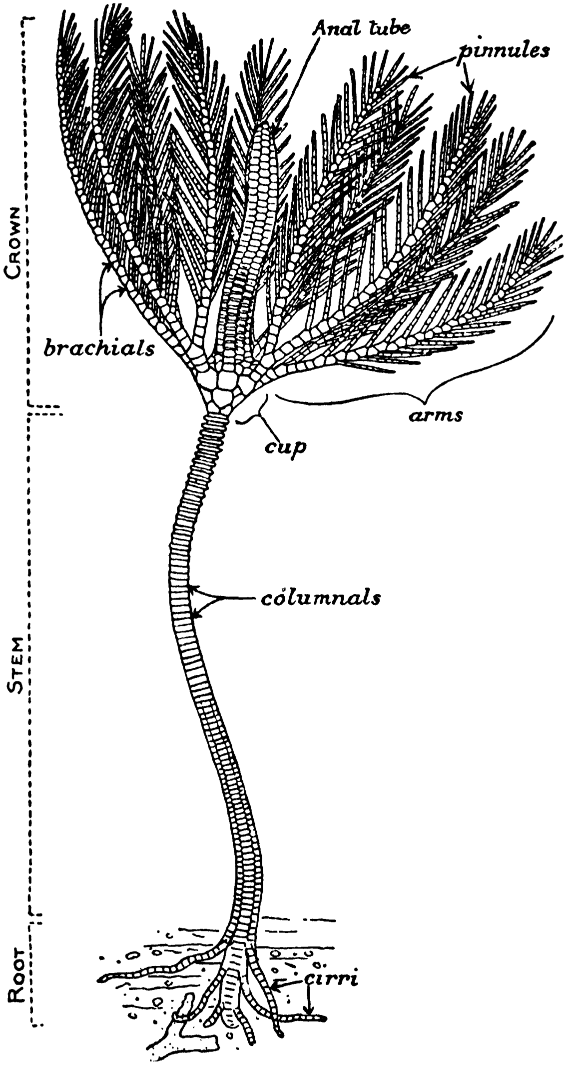


FIG. 144. Typical crinoid. (After Bather.)

plates, and is continued forward into five flexible arms, strengthened with other plates known as brachials. Accumulations of detached columnals and brachials form crinoidal limestone in the Carboniferous and other formations. The arms may branch repeatedly and may carry pinnules, jointed appendages that repeat the structure of the arms on a small scale.

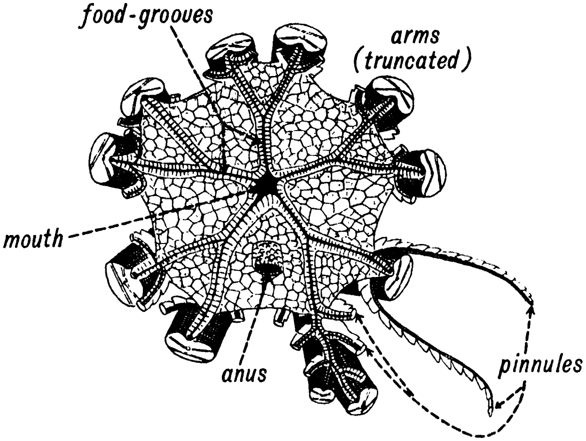


FIG. 145. Oral view of crinoid calyx, showing food grooves radiating from mouth, and ascending the ventral surfaces of arms and pinnules. (Modified after Müller.)

The mouth of a crinoid is situated on the upper surface (tegmen) of the calyx, within the circle of arms (Fig. 145). To compare a crinoid with a star-fish, you have to turn the latter on its back. From the mouth of the crinoid five food-grooves radiate over the tegmen and continue up the inner surface of the arms. They are supplied with tentacles(Fig. 146) which, like the tube-feet of star-fish and echinoids, are operated by a water-vascular system and act as sensory and respiratory organs. The food-grooves serve to convey food to the mouth by the action of cilia on their surfaces.

FIG. 146. Enlarged section of a crinoid arm showing, in addition to the parts labelled, the branching nerve cords and various hollow extensions of the body cavity. Brachial ossicle and cover plate in black; fleshy parts lined and stippled. (Modified after Bather.)

Crinoids range from the Palaeozoic to the present. Stalked crinoids attained their maximum development during the Palaeozoic. There is a tendency in later forms to lead a free existence for at least part of their lives, either using their arms to crawl on the sea-floor or floating freely in the open water, and often developing jointed cirri as temporary holdfasts. The genus *Marsupites* of the Upper Cretaceous is an example of a pelagic stalkless crinoid. The majority of living crinoids are stalkless.

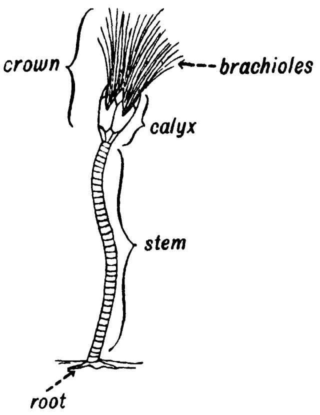


FIG. 147. Restoration of a blastoid, Pentremites. (After Berry.)

Other classes of Pelmatozoa are known only in the fossil state.

The BLASTOIDEA (Figs. 147–149), had the mouth on the upper surface of a bud-shaped calyx. Five food-grooves radiated from the mouth, each over a large plate (lancet-plate), and gave off at right angles numerous branches which continued up small arms or brachioles, that are seldom preserved. Under each lancet-plate ran two hydrospires, bundles of flattened lamellar tubes that are thought to have functioned in respiration, and possibly also in the discharge of genital products. Water gained access to the hydrospires through slits in the calyx plates or through pores in the side-plates that border the lancet plates. In the latter arrangement, the water, after passing

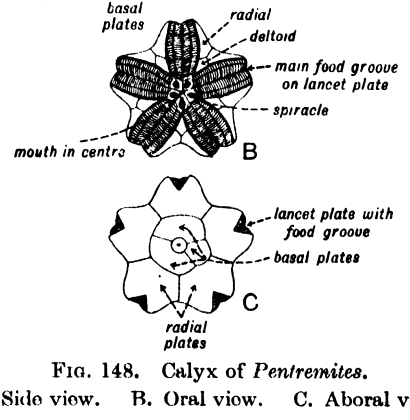


FIG. 148. Calyx of *Pentremites*.
A. Side view. B. Oral view. C. Aboral view.

along the hydrospires, was ejected at the spiracles, five holes grouped round the mouth at the top of the calyx. The hydrospires were doubtless ciliated.

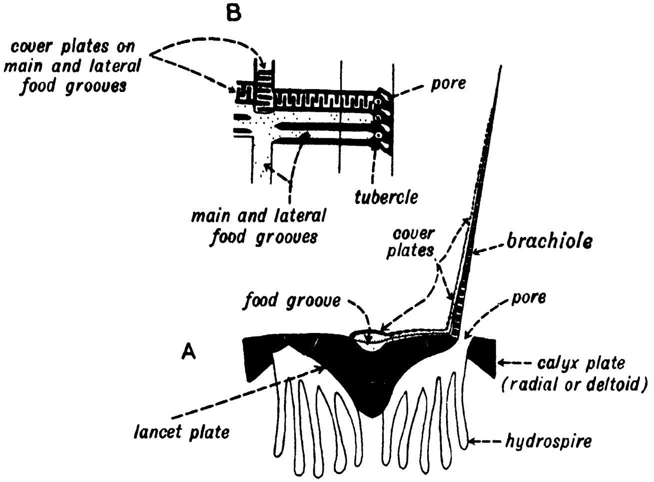


FIG. 149. *Pentremites.* (Modified after Berry.)

A. Section across ambulacrum.

B. Surface view of part of the large plate, showing main and branch food grooves. Much enlarged.

Blastoids occur most commonly in the Devonian and Carboniferous, but primitive forms go as far back as the Ordovician. They are found literally in millions in the Carboniferous Limestone of the Mississippi Valley.

The CYSTOIDEA included the most primitive fossil echinoderms. It is difficult to give a comprehensive diagnosis because they were so diverse in structure and in the external configuration of the calyx. They appeared in the early Cambrian and were extinct by the end of the Devonian. They are rare fossils and as a rule poorly preserved. In their most primitive types

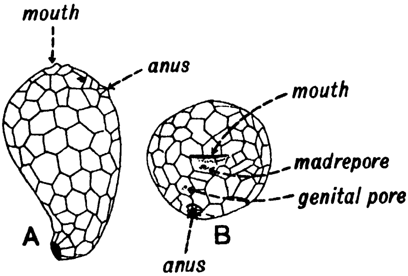


FIG. 150. *Aristocystis*, a primitive cystoid. (After Bather.)
A. Side view. B. Oral view.

(Fig. 150) the calyx was pear-shaped and the plates were irregular, both in outline and arrangement. Food-grooves were absent or not impressed on the calyx in these primitive examples, but were developed in the more advanced forms. At first they ramified irregularly over the surface of the calyx (Fig. 151), but later they straightened out, so that their bordering plates arranged themselves in definite ambulacral areas, while brachioles extended the food-grooves and increased the food-catchment area (Fig. 152). Systems of pores and folds in the substance of the plates probably functioned in respiration, and provide a basis for classification.

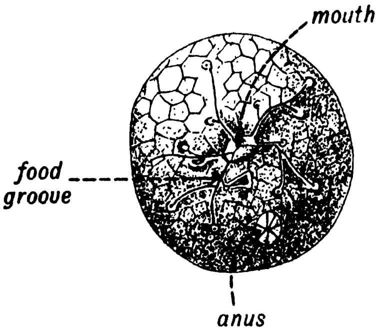


FIG. 151. *Glyptosphaera*, a spherical cystoid with irregularly branching food-grooves. (After Bather.)

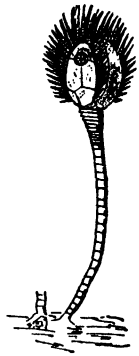


FIG. 152. *Lepadocrinus*, a stalked cystoid with brachioliferous food-grooves. (After Bather.)

The EDRIOASTEROIDEA ranged from Cambrian to Lower Carboniferous. Their remains are rare and badly preserved as a rule. The test varied from sac-shaped to flattened and was fixed by the under surface or entirely free; there was neither stalk nor arms. From the mouth in the centre of the upper surface five sinuous food-grooves radiated over the test (Fig. 153). These were floored by tiny ambulacral plates with pores between, and there were cover plates. The edrioasteroids stood rather apart from other fixed echinoderms. In some respects they resembled star-fish, but differed in having the spaces between the rays filled up with irregular plates, and in many of them being fixed by the under surface.

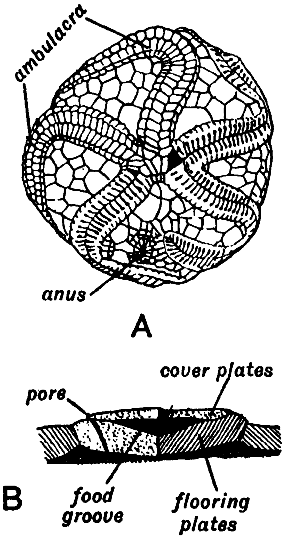


FIG. 153. *Edrioaster*. (After Bather.)

A. Oral surface. B. Section across an ambulacrum.

CHAPTER XLVI

VERMES AND ARTHROPODA

VERMES

Vermes (worms) constitute a group of structurally diverse phyla, rather than a single homogeneous phylum. They are not of great geological value, but they are of very great interest otherwise, especially one phylum, the Annelida (Fig. 138c), segmented worms. In segmentation the body is divided from front to rear by membranous partitions into a number of compartments, and each ring-like compartment or segment has essentially the same structural features as its neighbours, that is, the segments are serially homologous. For example, each segment typically bears a pair of short,

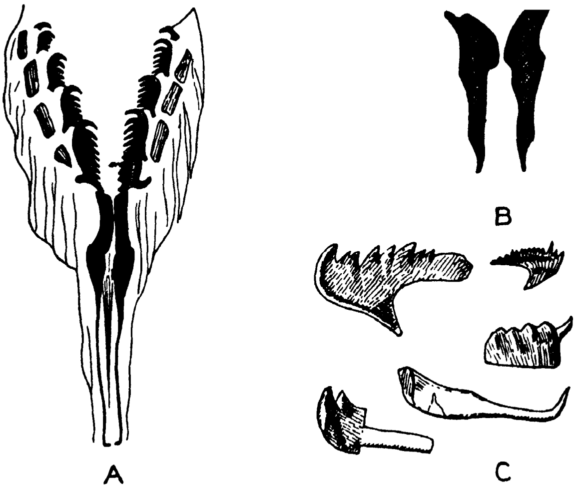


Fig. 154. A and B complete jaws of a modern annelid. Enlarged. (After Ehlers.)

A. Toothed plates (black) of upper jaw in chitinous jaw-sac.

B. Lower jaw.

C. Fossil annelid jaw-plates. The denticulated plates are detached from the jaw-sac after the death of the animal and drift apart. Enlarged. (After Hinde.)

thick, walking appendages, the parapodia. Some annelids have small horny jaws that are found fossil (Fig. 154). Others build limy tubes (Fig. 155) in which to live (e.g. *Serpula* and *Spirorbis*), and these are the commonest worm fossils, together with casts of tracks and burrows.

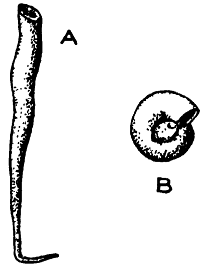


FIG. 155. Fossil annelid tubes. (After R. Etheridge, Jr.)
A. *Serpula.*
B. *Spirorbis.*

ARTHROPODA

The Arthropoda constitute one of the largest and most varied of the animal phyla, and have very numerous representatives at the present day, some of which markedly influence the health and happiness of man. The phylum includes lobsters, crabs, centipedes, spiders, ticks, scorpions, insects, and—most important of all from the geological point of view—the extinct trilobites of the Palaeozoic.

The arthropod body is segmented like that of an annelid worm, and the Arthropoda were certainly evolved from the Annelida. The Arthropoda have jointed appendages growing from the sides of the body. These are rigidly specialized for widely different functions according to the region of the body in which they are situated. For example, the first pair may be used as feelers (antennae) ; those round the mouth for grasping and cutting up food, and as weapons, like the claws of a lobster ; in the middle region of the body a variable number may be employed for walking or swimming, and others may be modified as gills for breathing. The different arthropod types have been evolved by varying the number of body-segments and combining them in different ways, and by adapting the appendages for many different functions.

There is an external skeleton consisting of a hardened epidermis of chitin. Growth can take place only during moulting, in the short time between the casting of the old covering and the hardening of the new.

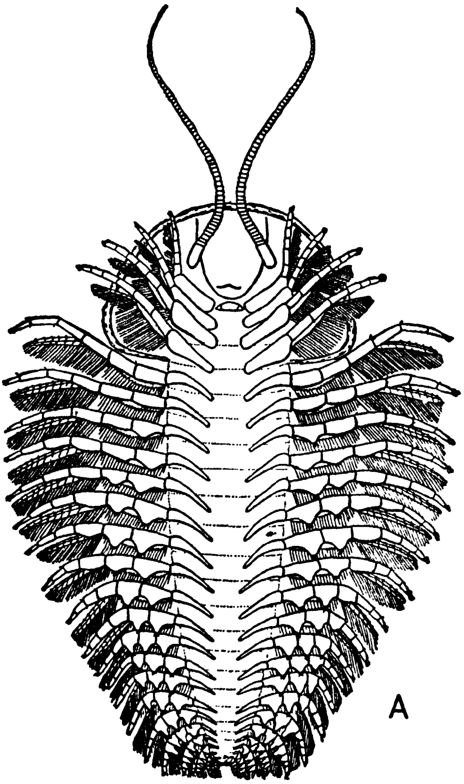
Classes : Crustacea, Arachnida, Myriapoda, Insecta.

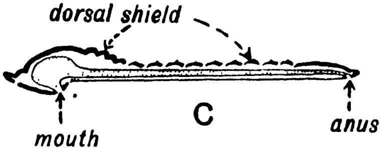
Fossils of the Myriapoda (centipedes, etc.) are rare, but occur in the continental Old Red Sandstone.

TRILOBITES.—Lobsters, shrimps, crabs, barnacles, etc. and the extinct trilobites (Figs. 280–3) are Crustacea—arthropods that are characterized by forked appendages, consisting of a basal part (protopodite or coxopodite) with two branches (exopodite and endopodite). In the trilobites the fringed exopodites (Fig. 156) were used for swimming and probably also as gills in which the blood was oxygenated. The coxopodite projects inwards to form an endobase ; endobases in the cephalic region, being employed for cutting up food, are known as gnathobases. In living crustacea there are two pairs of antennae in front of the mouth; in trilobites only one pair has been discovered.

The segments of the body may be grouped into three regions: head (cephalon), thorax, and abdomen, though in modern crustacea head and thorax are generally combined to form a cephalo-thorax covered by a chitinous plate (carapace) strengthened by lime salts. The carapace is usually a single piece, situated dorsally, but it may consist of two pieces, or valves, one on each side of the body, as in the Ostracoda; or it may form a pyramid of calcareous plates as in the barnacles, which are fixed in adult life and so profoundly modified that they are utterly unlike other crustacea—their free-swimming larval phase indicates their true affinities.

The trilobites are by far the most important fossil Arthropoda; they were exclusively marine, living mainly near the sea-floor in shallow, clear water.





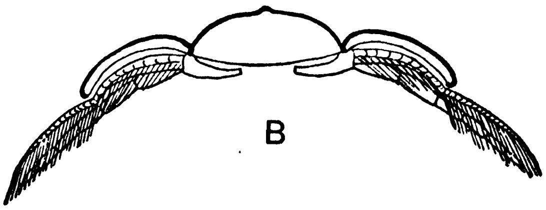


FIG. 156. Trilobites. (A and B after Beecher, C after Berry.)

A. Ventral view, showing appendages.

B. Transverse section of thoracic region, showing relation of the appendages to the dorsal shield.

C. Longitudinal section, showing alimentary tract.

Various specializations, however, indicate occasional adaptation to other conditions; for example, the extravagant development of spines in some stocks probably indicates a free-floating existence in the open sea. With the brachiopods and graptolites they are the most important fossils of the Lower Palaeozoic; the faunal subdivision of the Cambrian system is based on the trilobites. The segmented trilobite body (Fig. 156A, B) had tripartite divisions, not only antero-posteriorly into head, thorax, and abdomen, but also transversely into axial and lateral lobes. The latter trilobation is denoted by the name of the sub-class (Trilobita). The segments of the head were fused to form a head-shield (cephalon), and those of the abdomen were typically fused to form a tail-piece or pygidium. Thoracic segments were free and sometimes movably articulated, so that the animal could roll up for protection of the soft under parts. Rolled up trilobites are often found and furnish very attractive fossils. The crustacean nature of trilobite appendages was discovered by sectioning rolled-up individuals. Afterwards very perfect individuals with the appendages in the normal position were found in the Utica Shale of New York.

The structure of the cephalon has recently been utilized, to the exclusion of the other features, in the ordinal classification of the trilobites. The transverse furrows, often present on its axial portion, or glabella, are traces of original cephalic segmentation. The lateral parts of the cephalon, known as 'cheeks', were usually divided each into a 'free' outer portion and 'fixed' inner portion by an ecdysial line, the facial suture, which ran from in front of the glabella, along the inner (axial) side of the large compound eye, to the margin of the cephalon either in front of the genal angle (proparian condition) or behind it (opisthoparian condition). Eyes and facial sutures may be absent.

Eucrustacea.—The remaining crustacea, grouped together as Eucrustacea, true crustacea, furnish a number of important fossils.

The Branchiopoda, minute 'water-fleas' that swarm in fresh, brackish, and super-saline waters, have bivalved shells and leaf-shaped appendages for swimming; the appendages also carry gills—hence the name Branchiopoda ('gill-footed'; *cf.* the unrelated Brachiopoda, 'arm-footed'); they are also called Phyllopoda, in reference to the leaf-like form of the appendages.

An important genus is *Estheria* (Fig. 157A), which abounds at the present day in temporary pools in the South African desert and occurs at

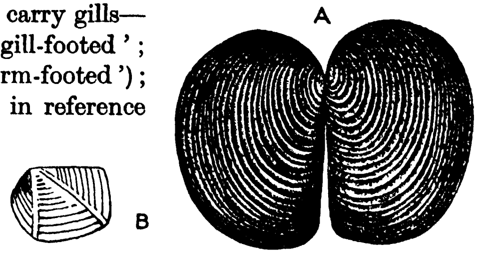


Fig. 157. Fossil branchiopods. Enlarged. (After Rupert Jones.)
A. *Estheria*. B. *Leaia*.

various horizons from Devonian onwards. The carapace of *Estheria* with its concentric ridges has a superficial resemblance to the shell of certain bivalve molluscs (e.g. *Posidonia*), but its ridges are quite distinct from growth lines, because the carapace of *Estheria* grows by moulting as in other Crustacea, and not by increment as in a lamellibranch; also the carapace of *Estheria* is made of chitin and not calcium carbonate.

The OSTRACODA, like the Branchiopoda, are minute bivalved Crustacea, but the appendages are not leaf-like. They range from Upper Cambrian to present, and are numerous at certain horizons in the Carboniferous. The small shells vary greatly in form (Fig. 158), although an ovate or reniform shape is common; the ornament of the valves is exceedingly variable and often elaborate.

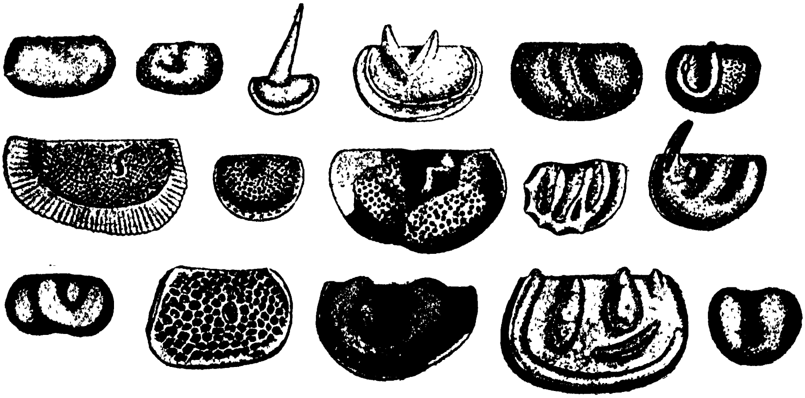


FIG. 158. Various fossil ostracods. Much enlarged. (After Zittel-Eastman.)

The MALACOSTRACA are the large Eucrustacea, including lobsters and crabs. Some familiar Palaeozoic forms belonged to the order Phyllocarida (Fig. 159). The carapace of the Phyllocarida may be bivalved, or it may be single and down-folded at the sides. The last segment of the abdomen, the telson, is furnished with pointed spines.

The ARACHNIDA are represented at the present day by scorpions and spiders. The anatomy of the scorpion may be taken as typical (Fig. 160). There is a short cephalo-thorax (prosoma), and a long abdomen divided into two regions, an anterior containing six broad segments (mesosoma) and a posterior with six narrow segments (metasoma). The telson in the scorpion forms a highly poisonous sting. There are no appendages in the metasoma.

The arachnids are divided into two sub-classes—terrestrial and aquatic. The terrestrial include the scorpions and spiders and are not common fossils,

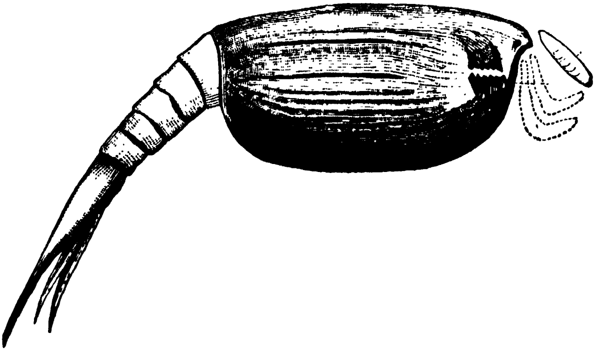


FIG. 159. *Ceratiocaris*, a Palaeozoic phyllocarid crustacean. (After Woodward.)

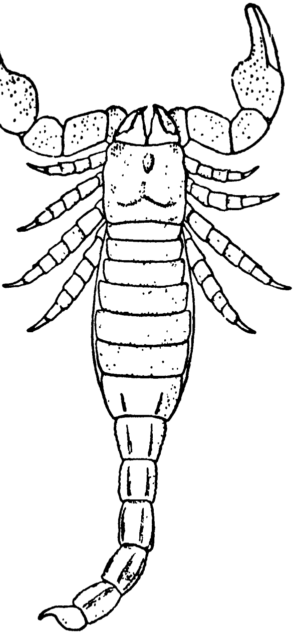


FIG. 160. *Palaeophonus*, a Silurian scorpion. (After Pocock.)

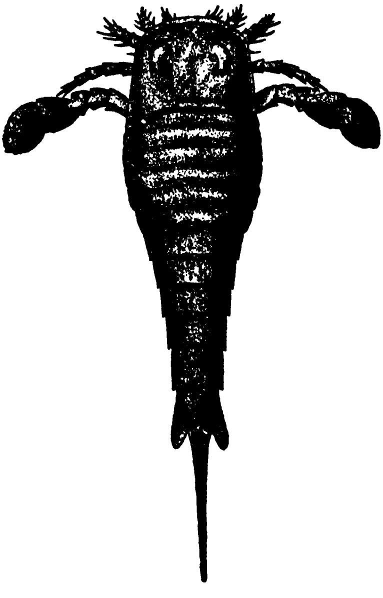


FIG. 161. *Eurypterus*. (After Schmidt.)

though it may be pointed out that an ancestral scorpion, *Palaeophonus* (Fig. 160), found in the Silurian of Lesmahagow (Lanarkshire) and Gotland, appears to have been marine. The aquatic forms (Merostomata) may be considered under two groups—the Eurypterida and Xiphosura.

The EURYPTERIDS were the most formidable creatures of the Lower Palaeozoic, reaching a length of 10 feet in some cases. Reference may be made to two genera—*Eurypterus* (Fig. 161) and *Pterygotus* (Fig. 162). In *Eurypterus* the last pair of limb-appendages were shaped like paddles, and the telson was furnished with a long spine. In *Pterygotus* one pair of the oral appendages formed strong claws and the telson consisted of a divided oval plate. Eurypterids seem to have started as marine animals, but to have become adapted to fresh water in Old Red Sandstone and Carboniferous times.

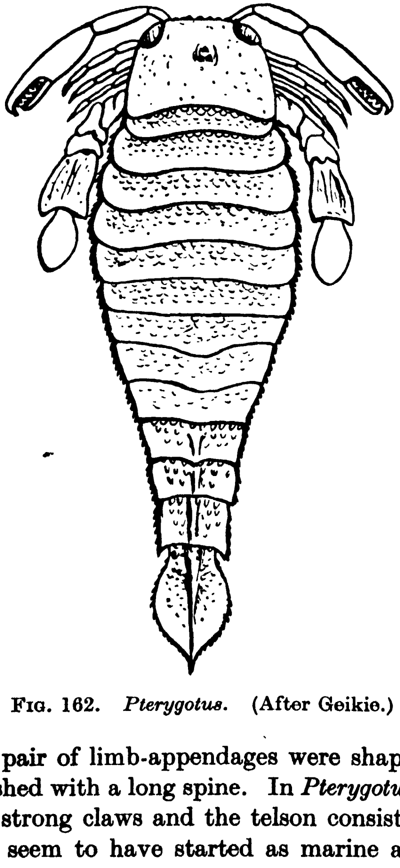


FIG. 162. *Pterygotus*. (After Geikie.)

The XIPHOSURA include the only living marine arachnid—the King or Horseshoe ' Crab ', *Limulus*, which ranges from Trias to present day (Fig. 163). Certain Xiphosura are not uncommon in the Coal Measures (Fig. 165). The body is trilobed and shortened by consolidation of the abdominal segments, and there is a long spine-like telson. Trilobation of the body is especially distinct in the Palaeozoic forms and in the embryo of *Limulus*. The latter, before the development of a long tail-spine is remarkably like a trilobite (Fig. 164). Shortening of the body and absence of differentiated mesosoma and metasoma are also characteristic of the spiders.

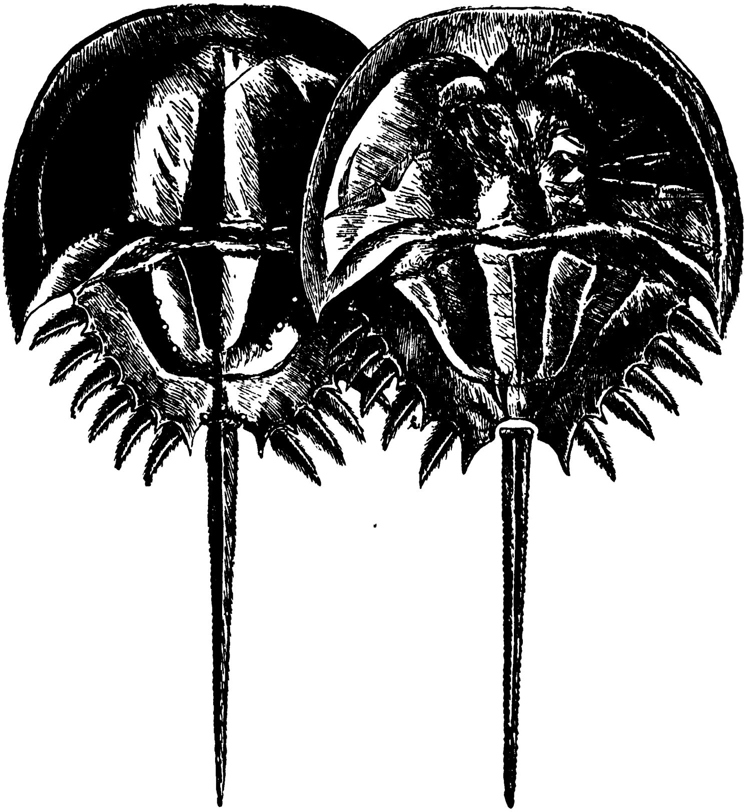


Fig. 163. A Jurassic *Limulus*. (After Zittel.)
Dorsal and ventral aspects.

The Insecta have head, thorax, and abdomen clearly differentiated. The thorax bears three pairs of appendages for walking (hence the alternative name Hexapoda). The insects are the only invertebrates that have conquered the air, and for this purpose wings are developed on the second and third thoracic segments. These wings are not homologous with the wings of a bird, which are modified fore limbs. The insect's wing sprouts from the back, and consists of a very thin double film of chitin, enclosing a fine layer of living tissue. As the wing is made of chitin it is capable of fossilization (Fig. 166), and beautifully preserved specimens, sometimes associated with the fossilized body, have been found in rocks as old as the Coal Measures. These Coal Measures occurrences are the earliest records of insects in the rocks, apart from examples in the Rhynie chert (Aberdeenshire) of Devonian age. Insects are frequently found entirely mummified in amber of Oligocene age from the Baltic region. Like the spiders, insects breathe air by means of a system of tubes that ramify through the body.

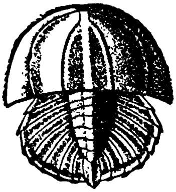


FIG. 164.—The trilobite-like embryo of a modern *Limulus*. (After Dohrn.)

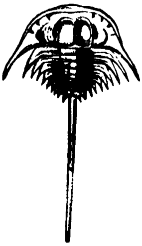


FIG. 165. *Belinurus*, a xiphosuran from the Coal Measures. (After Woodward.)

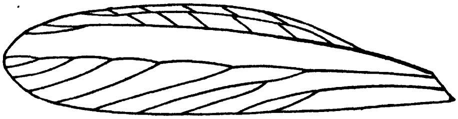


FIG. 166. An insect's wing from Permian rocks. Enlarged. (After Zalessky.)

CHAPTER XLVII

BRYOZOA (POLYZOA) AND BRACHIOPODA

BRYOZOA

BRYOZOA are mostly marine, but some live in fresh water. At first sight they look like coelenterate polyps, for they are small animals that form colonies by budding and each individual has a circlet of respiratory tentacles (lophophore) surrounding its mouth (Fig. 167). They are, however, much more elaborately organized than coelenterates. Each zooid has a U-shaped digestive tract, ending in an anus that lies either within or without the ring of tentacles. It also has a central nervous system consisting of a single nerve centre, situated between gullet and intestine. The body wall of each individual is hardened externally by chitin or $CaCO_3$, to form a cell-like, box-like or tubular chamber (zooecium) as a protective covering into which the tentacles can be withdrawn when the animal is alarmed. This covering or skeleton can be fossilized. The external form of the zooarium (the entire

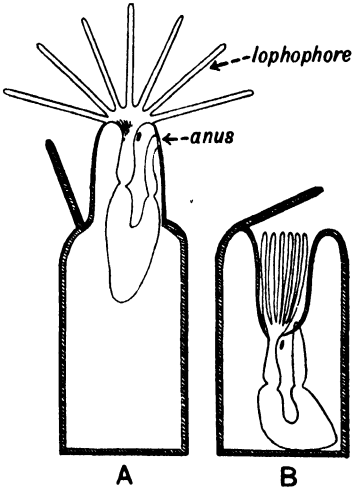


FIG. 167. Bryozöon in its zooecium. Enlarged. (After Boas.)

A. Tentacles of the lophophore extended.
B. Tentacles withdrawn into the protection of the zooecium.

skeleton of the colony) is infinitely variable. It may be massive and nodular; or it may be branching and reticulate, as in *Fenestella* (Fig. 168), which is common in the Carboniferous; or moss-like (hence the name Bryozoa—moss animals) forming an incrustation on sea-weed, rock and shells (Fig. 169).

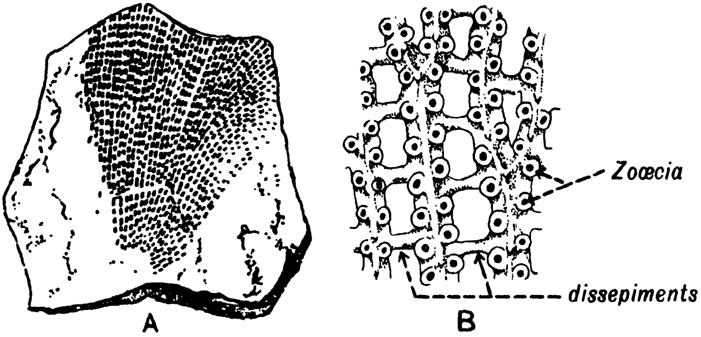


FIG. 168. *Fenestella*, a Palaeozoic bryozöon. (After Bassler.)
A. Portion of zooarium, showing non-celluliferous surface.
B. Part of the celluliferous (zooecial) surface. Enlarged.

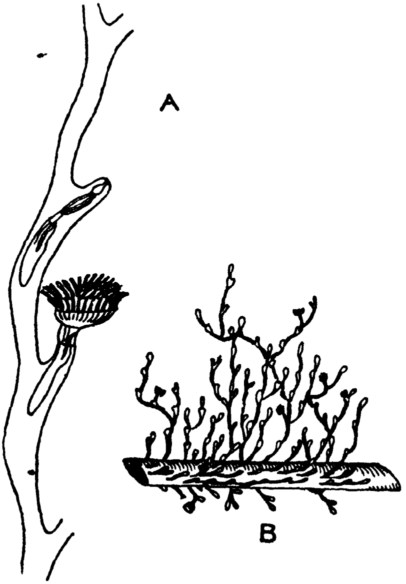


FIG. 169. Fresh-water bryozöon. (Modified after Allman.)
A. Portion of zooarium enlarged.
B. Moss-like colony encrusting piece of wood.

BRACHIOPODA

The general anatomical organization of the Brachiopoda is similar to that of the Bryozoa, and there is a lophophore. For these reasons the brachiopods are sometimes united with the Bryozoa into a single phylum, the Molluscoidea. The differences, however, are perhaps more striking than the resemblances. The brachiopods are not colonial animals like the Bryozoa, but live as separate individuals, each enclosed in a shell consisting of two valves (Figs. 282B, 286C, 288C, G, H, 298A, 303, 309). They pass their adult life attached to the sea-floor by a fleshy muscular stalk (pedicle) that is simply a backward extension of the body passing through an aperture in the shell (Figs. 170, 171A-D). In primitive forms this aperture may be shared by both valves, but is more usually confined to the ventral, or pedicle, valve. The pedicle may emerge near the centre of the ventral valve, with resulting mushroom-like growth of the whole organism (Fig. 171D); or, with the ventral valve produced backward into a beak, the pedicle may emerge from a triangular aperture (delthyrium) on its dorsal aspect (Figs. 170, 171C). The delthyrium may be partially closed by calcareous plates that have an elaborate and sometimes confusing terminology. This type of pedicle emergence, when associated with a short pedicle, causes the brachiopod to be

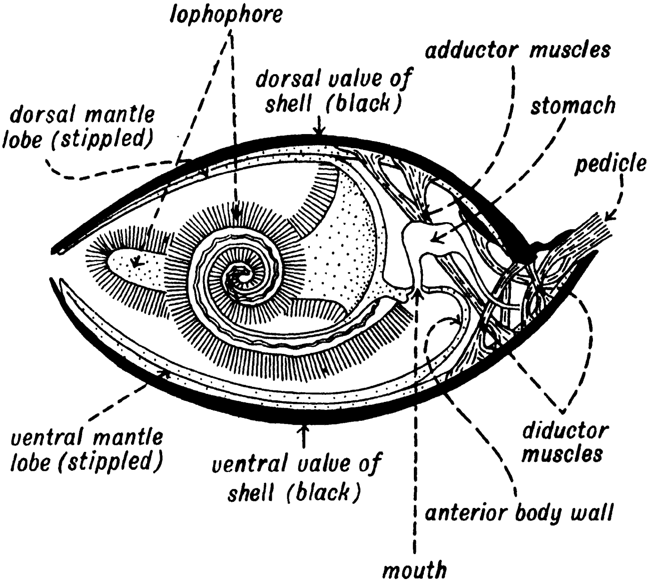


FIG. 170. Median longitudinal section of a brachiopod, to show the general relationship of soft parts to shell. Thickness of mantle lobes and anterior body wall exaggerated.

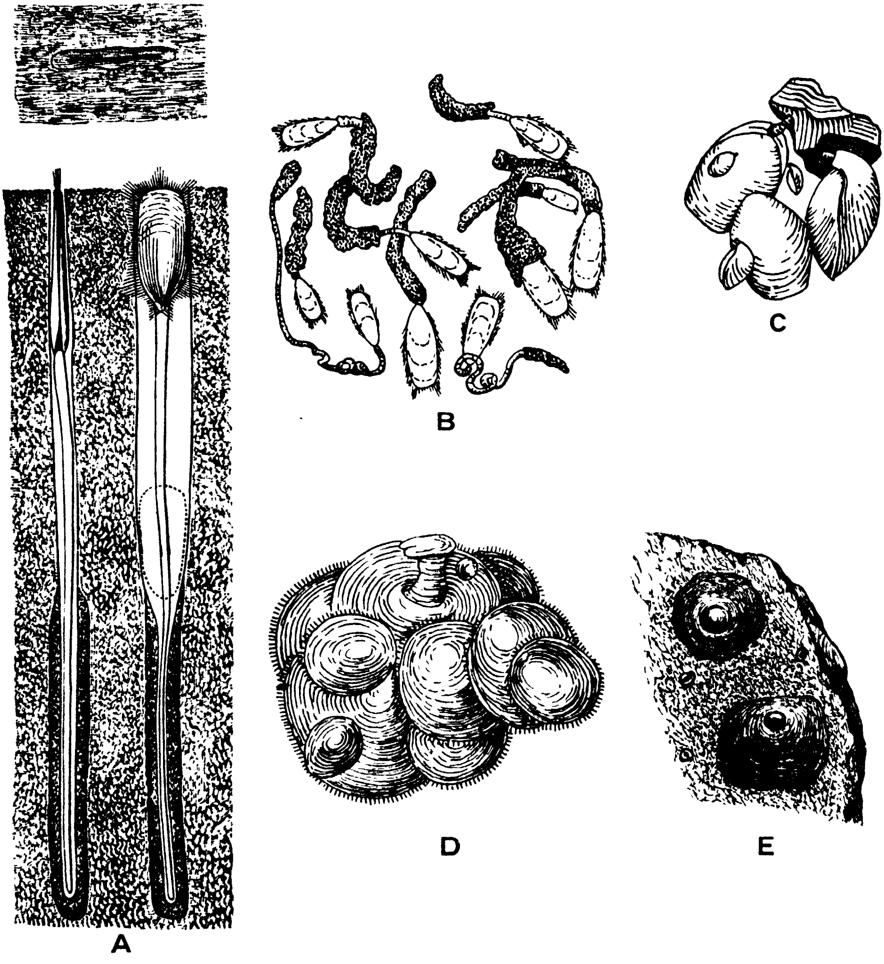


FIG. 171. Environment and attitude of shell in various Brachiopoda.

A. *Lingula* in its burrow. The upper figure shows the trilobed aperture of the burrow ; the three lobes correspond to the lateral (incurrent) and median (excurrent) tubes formed by the anterior setae of the mantle. (After François.)

B. Specimens of the lingulid *Glottidia* free from their burrows and having the sand-tube (cf. dark shading in A) adhering to the extremities of the long worm-like pedicles. (After Morse.)

C. A group of terebratellids showing attachment by short pedicle. (After Davidson.)

D. Mushroom-like growth of a cluster of discinids, one individual turned over to show pedicle emerging from approximately the centre of the ventral valve. (After Davidson.)

E. *Crania.* Atrophy of pedicle leads to cementation by entire surface of ventral valve. (After Shipley.)

recumbent on the dorsal valve (Fig. 171c). *Lingula* and its relatives, with their long, worm-like pedicle, burrow in sand or mud, and retain a limited power of free movement (Figs. 171, A and B). In some brachiopods, on the other hand, the pedicle is atrophied, and fixation is achieved by spines or by direct cementation of one valve (Fig. 171E). The generally accepted classification of the brachiopods into orders is based on the nature of the pedicle aperture and its associated structures, and on the stages of shell development.

The lophophore has two long fleshy spiral appendages (Figs. 170, 172), the so-called arms (brachia). These brachia give the name to the phylum; Brachiopoda means arm-footed, from a mistaken idea of the early zoologists that the brachia were homologous with the muscular locomotive organ of the mollusca that is miscalled the foot. The brachia have a ciliated gutter, fringed with tentacles that can curve over to transform the gutter into a closed conduit for food-carrying currents of water (Fig. 173). In one order only, the Telotremata, the latest and most specialized of the brachiopods, the brachia are provided with ribbon-like calcareous supports that form loops or spirals.

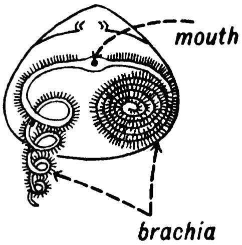


FIG. 172. Diagram illustrating the relation of the lophophore with its spiral brachia (one of which is extended) to the mouth of a brachiopod. (After Owen.)

The shell is secreted partly by the surface of the body and partly by very thin, membranous, forward extensions of the body wall, the dorsal and ventral mantle lobes (Fig. 170). The main part of the animal's body, containing the principal muscles and viscera, occupies only a small posterior portion of the shell cavity. The anterior body wall, with the mouth and lophophore in the centre, forms an inclined diaphragm in the shell cavity; and in front of this the whole anterior part of the shell cavity is occupied by the brachia.

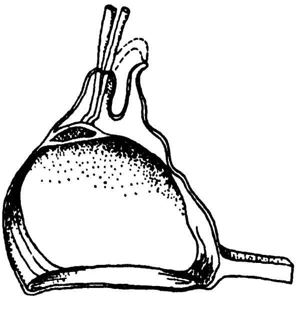


FIG. 173. Cross-section of median spiral arm in *Magellania*, a recent terebratellid. (After Hancock.)

Brachiopod shells are made of chitin or calcium carbonate. In the chitinous forms, which are more primitive, the two valves are held together by the muscles that open and close the shell. In calcareous shells the valves are rigidly articulated by a system of processes and cavities called the hinge, so that movement can take place only in one plane (Fig. 174). Two of the processes, called teeth, are situated in the ventral valve below the beak, and between them may be inserted a more or less well-developed projection of the dorsal valve, the cardinal process. The teeth fit into cavities of the dorsal valve on each side of the cardinal process. The shell is closed by the contraction of two adductor muscles, which are attached to the inner surfaces of the valves and divide in crossing the shell cavity (Fig. 170), giving four scars in the dorsal valve (Fig. 174). The shell is opened by the contraction of four diductor muscles, which are affixed to the inner surface of the ventral valve and to the cardinal process of the dorsal valve (Fig. 174).

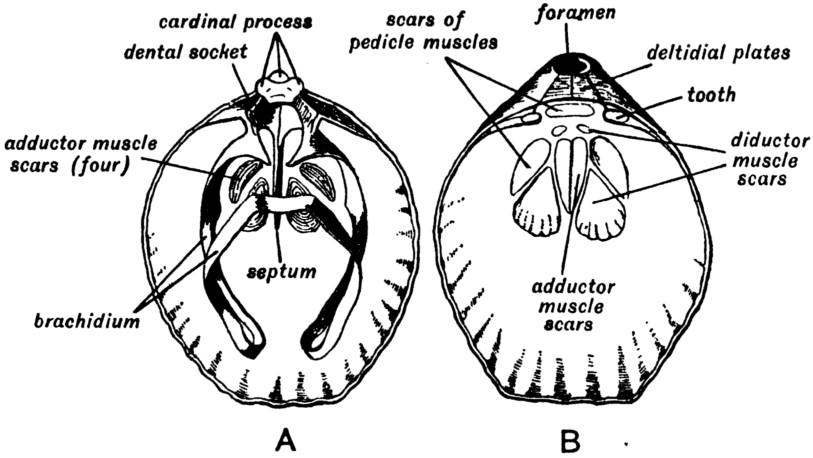


FIG. 174. Internal aspects of a recent brachiopod shell (*Magellania*). (After Davidson.)
A. Dorsal valve. B. Ventral valve.

In the hingeless (inarticulate) forms the shell may be circular, oval or ovate in outline. The hinged (articulate) shells may be semicircular or subquadrate, with straight wide hinge-line; or ovate, with short and curved hinge-line. The valves are usually unequal and bilaterally symmetrical, the ventral usually larger than the dorsal. Both may be convex; or one may be convex and the other flat or even concave.

Brachiopods are of enormous geological importance. The decline of the phylum has been continuous since the lower Palaeozoic, and, although four orders are represented at the present day, genera and species are now few.

CHAPTER XLVIII

MOLLUSCA

The phylum Mollusca includes oysters, mussels, cockles, whelks, snails and slugs, squids, cuttle-fish, and octopus.

The name Mollusca means soft-bodied, and is rather a misnomer for animals which, although soft-bodied, generally secrete a hard shell. The name ' shell-fish ' by which the shell-bearing aquatic forms are generally known, is even more confusing, since the true fish are vertebrates.

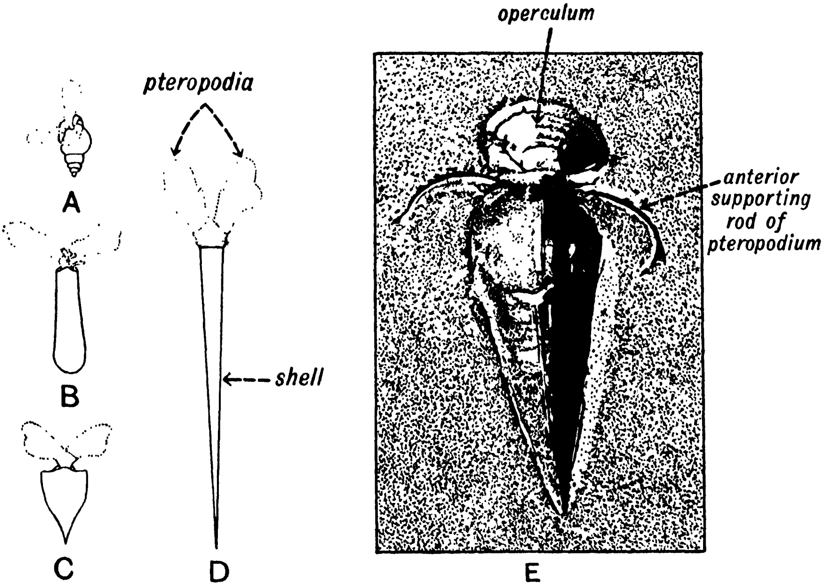


Fig. 175. A-D. Various recent pteropods. (After Murray.)
E. *Hyolithes*, a Palaeozoic pteropod, with supporting bars of the pteropodia preserved. (After Walcott.)

Although they are endlessly varied in their adult form and in their adaptations to different modes of life, the Mollusca all conform to a characteristic and readily recognisable structural ground-plan. The body is unsegmented and bilaterally symmetrical, and on the under surface there is a mass of muscle used for locomotion, and therefore called the ‘ foot ’ (Figs. 175, 176, 184, 185). This organ is variously modified in different forms for crawling, burrowing, or swimming. The integument of the dorsal surface is produced into a fold, which has free edges like a skirt, and is called the mantle (pallium) (Figs. 176A, 179, 180, 184, 190). The space between the mantle and body (the mantle cavity) contains the gills. The epidermis of the mantle and the dorsal part of the body usually secrete a calcareous shell of one or more pieces.

The body surface is richly supplied with nerves, and with cells that secrete the abundant mucus that is such an unpleasant feature of the live animal. The alimentary, circulatory, nervous and generative systems are well developed.

The Mollusca originated in shallow seas, and the majority have remained aquatic and marine. The terrestrial forms are restricted to only a few groups of snails and slugs that are individually numerous. The Mollusca vary in size from the almost microscopic to the 500 lb. clam of the Pacific and the giant squid of the North Atlantic, a fierce and active carnivore measuring over 50 feet across extended tentacles.

There are three main classes : Gastropoda, Cephalopoda, Lamellibranchia.

The GASTROPODS are the whelks, limpets, etc. and the terrestrial snails and slugs. The foot forms a flat sole on the under surface of the body, suitable for the crawling movements with which we are familiar in the snail.

The classification of the gastropods into major groups is based on the structure of the nervous system and gills, as affected by the torsion of the

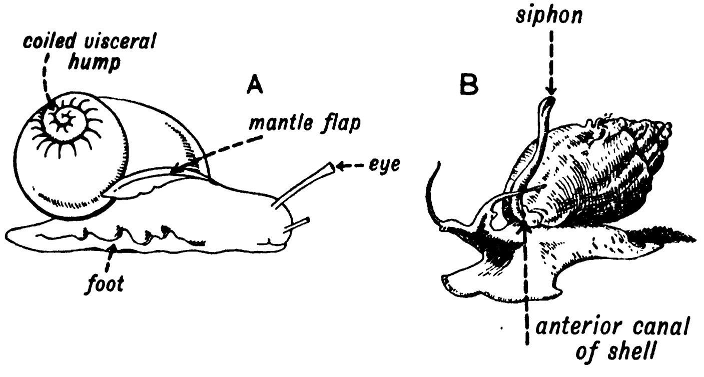


FIG. 176. A. Gastropod with shell removed to show coiled visceral hump. (Modified after Graham Kerr.)

B. *Buccinum*, showing shell in position over visceral hump. (After Wells, Huxley and Wells.)

viscera during larval development—a phenomenon peculiar to Gastropoda. It is not always possible to assign fossil shells with confidence to a place in this classification, based as it is entirely on perishable structures, and unfortunately no alternative major classification of the gastropods with sole reference to shell structure has been found possible.

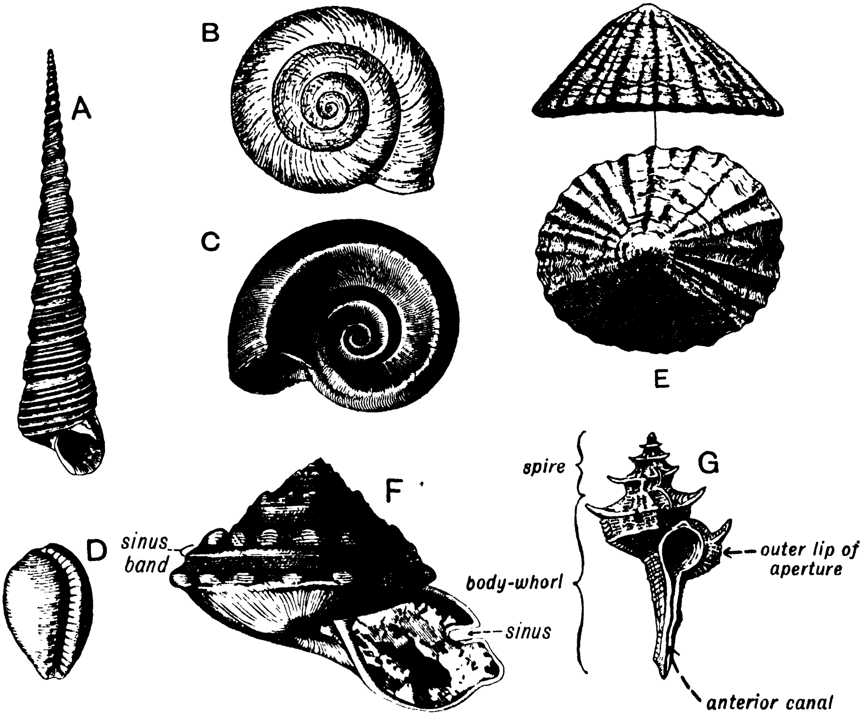


Fig. 177. Various gastropod shells.

A. *Turritella.*
B. *Planorbis.*
C. *Euomphalus.*
D. *Cypraea.*
E. *Patella.*
F. *Pleurotomaria.*
G. *Murex.*

Most gastropods have a one-valved shell moulded on to a visceral hump ; in many gastropods this hump tends to become a very high and narrow cone, and in consequence coils upon itself in a screw spiral, which is the most stable form that a long and soft structure in the situation of the visceral hump could assume (Fig. 176). The shell in these cases adopts the same screw spiral form. The fundamental geometrical plan of the hollow spiral cone is reproduced in an almost infinite variety of ways by gastropod shells. The spire may be high, with many turns, or whorls, as in *Turritella* (Fig. 177A), or it may be so much depressed that the shell is discoidal, as in *Planorbis* (Fig. 177B) or

Euomphalus (Fig. 177C). The body-whorl, into which the animal withdraws, may grow so large as to envelop the earlier whorls of the spire (*Cypraea*, Fig. 177D), or the spiral nature of the cone may be obscured by the relatively rapid growth of the shell-aperture (*Patella*, the limpet, Fig. 177E). Coiling may be in a plane spiral, giving symmetrically discoidal or globular shells (Bellerophontidae ; Fig. 178). The shape of the aperture has an important influence on the form of the shell. It is commonly subcircular or ovate, but it may be slit-like, extending the entire length of the shell (*Cypraea*). Its outline may be interrupted by arrangements for directing water into or out of the mantle-cavity. In forms with paired gills like *Pleurotomaria* (Fig. 177F) and the extinct *Bellerophon* (Fig. 178), an exhalent slit in the mantle is symmetrically placed between the gills and produces a corresponding fissure or sinus in the outer lip of the shell. The filling of this fissure with shelly matter during growth produces the characteristic sinus-band. In the forms which have only one gill left after torsion of the viscera, the anterior edge of the mantle may be produced into a more or less elongated inhalent tube or ' siphon ' for directing currents of water to the gill (*Buccinum* ; Fig. 176B). The corresponding part of the shell is moulded round the siphon to form the 'anterior canal' (*Murex*; Fig. 177G). In addition there may be an exhalent (anal) canal at the posterior extremity of the aperture.

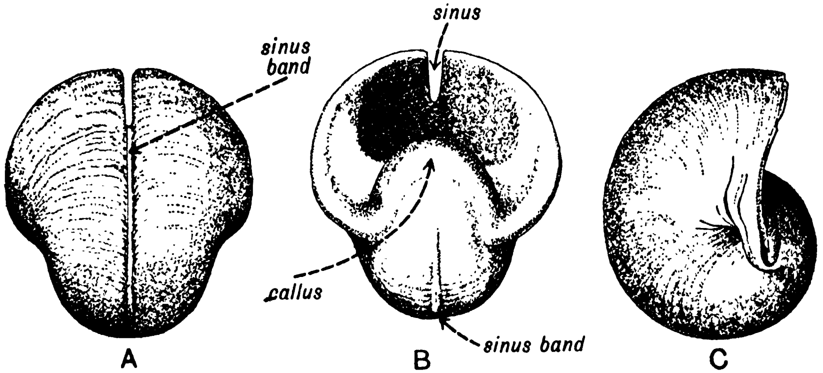


FIG. 178. A Carboniferous *Bellerophon*.
A. Dorsal view. B. Apertural view. C. Lateral view.

Some marine gastropods swim freely at the surface of the sea, instead of crawling on the sea-floor like the majority of marine snails. For this type of life the foot is expanded into wing-like lobes (pteropodia ; Fig. 175), by means of which the animal swims near the surface of the open ocean in a movement that suggests the flight of a butterfly ; hence the Pteropoda (wing-footed) are often called sea-butterflies. They rise to the surface towards nightfall in vast swarms. Their very thin and delicate shells are hollow cones of varied shape, and they may accumulate in great quantities on the sea-floor as pteropod ooze.

Gastropods occur in Cambrian and later rocks. They are specially numerous and useful fossils in the Kainozoic and are apparently at their maximum at the present day.

Nautilus (Fig. 179), cuttle-'fish' (Fig. 180), octopus, etc., and the extinct ammonites (Fig. 181, A-C, G-I) and belemnites (Fig. 182, B and C) are all included in the class CEPHALOPODA. They are all marine and less familiar than lamellibranchs and gastropods, because the comparatively few living species are active swimmers whose remains do not constantly occur in the debris of recent beaches. Cephalopods are the most highly organized molluscs and include the largest invertebrate, the giant squid of the North Atlantic. The flexible 'arms' or tentacles surrounding the head, with their powerful suckers for catching prey, are generally regarded as homologous with the foot of other molluscs, hence the name, Cephalopoda. Cuttle-fish swim slowly by undulating a fin-like fold (Fig. 180) that surrounds the body, but they can also move with great rapidity by violently ejecting water from the mantle cavity through a ventral funnel (hyponome; Figs. 179, 180). In *Nautilus* the hyponome is seen in its primitive condition as an enrolled mass of muscle (Fig. 179), which could doubtless be unrolled for crawling and may be the true homologue of the foot of other molluscs. In many fossil cephalopods an embayment called the hyponomic sinus was

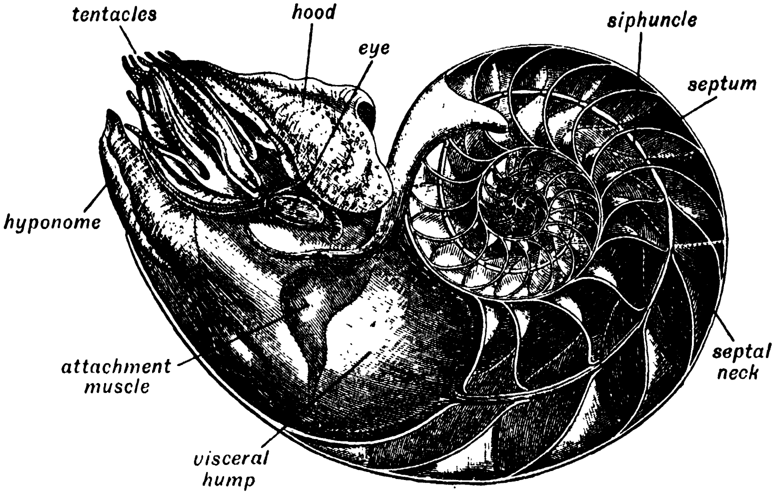


FIG. 179. *Nautilus*, with shell sectioned to show chambers and siphuncle. (After Owen.)

formed by the funnel in the ventral margin of the aperture, with corresponding sinuosity of the ventral growth lines. The absence of this sinus and its replacement by a rostrum in many ammonites (Fig. 181A) is hardly justification for asserting that these did not possess a hyponome.' Some cephalopods have the power of covering their retreat by ejecting a cloud of inky fluid (sepia), which is sometimes found fossil.

Nautilus lives in the tropical Pacific, near the bottom, at depths up to 2,000 feet, and comes to shallow water only at night. Some of the large squids swim at various depths in the open ocean, others live near land, and some are gregarious. Modern cephalopods are carnivorous. Nothing definite can be said about the habits of extinct forms. The variety of shell-form suggests that some lived like *Nautilus* and the modern squids, that some were bottom-crawlers, and that others were nektonic or plantonic in diverse curious ways.

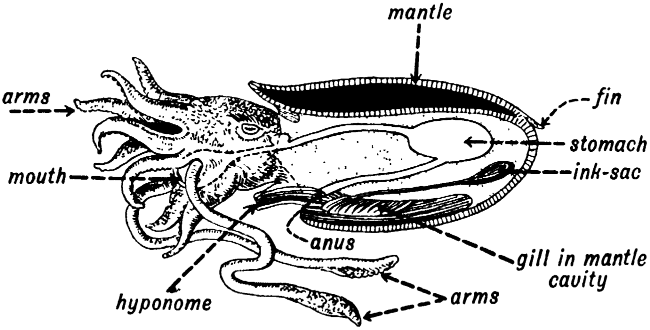


FIG. 180. Cuttle-fish, *Sepia*, sectioned behind the head to show the general internal anatomy and the dorsally situated internal shell or "cuttle-bone" (black). (Modified after Schmeil.)

Modern cephalopods are classified on the basis of the number of gills into Tetrabranchia (comprising only one genus, *Nautilus*), and Dibranchia (all the other modern cephalopods, with internal shells, like *Sepia*, or without shells). By some authorities the extinct ammonites are regarded as tetrabranchs because they have a chambered shell like *Nautilus*, and the extinct belemnites are included in the dibranchs, because the belemnite shell was obviously an internal structure like the shells of modern dibranchs. The gills, however, are soft structures not preserved in the fossil, and the following classification is better suited to palaeontological requirements :

Nautiloidea : the modern tetrabranchiate *Nautilus* and its fossil forbears.
Ammonoidea : the ammonites.

Coleoidea: the modern dibranchiate cephalopoda, divided into Decapoda with ten arms (two being longer than the others, Fig. 180), Octopoda, with eight arms of nearly equal size, and the extinct order Belemnoidea (the belemnites).

The shell in most cases is a chambered cone, which, so long as it is external, offers a place of retreat, the animal withdrawing into the last chamber (body chamber), which is then sealed in *Nautilus* by the fleshy hood (Fig. 179). In the ammonites two calcareous plates or, alternatively, a single horny plate, doubtless carried in the same position as the hood of *Nautilus*, acted as an operculum for closing the body chamber. The double calcareous operculum is called aptychus (Fig. 181B); the single horny plate is the anaptychus. The shell is usually coiled in a plane spiral, as in *Nautilus* and the ammonites, but may be straight as in some of the Palaeozoic forms (Fig. 182A). The animal in the body chamber maintains connection with the vacated chambers of the shell by means of a fleshy, tubular prolongation of the mantle, the siphuncle, which passes through funnel-like septal necks (Fig. 179) in the partitions (septa) of the shell. The septal necks may be extended to form a continuous and typically tubular sheath for the siphuncle. In the Palaeozoic nautiloids, however, siphunclar form and structure were varied and often complex. The vacated chambers of the shell in *Nautilus* are filled with gas secretion, the control of which, doubtless a function of the siphuncle, probably serves to adjust the specific gravity of the body to that of the surrounding water, so that the animal does not have to expend energy continuously to keep from sinking.

In *Nautilus* and many of the Mesozoic and Upper Palaeozoic Nautiloids the septal necks are near the centre of the septa (Fig. 179). In the Nautiloidea of the Lower Palaeozoic, however, they were sometimes central, sometimes excentric or marginal, and in adults of the Ammonoidea, a marginal position, dorsal or ventral, became typical. In the dorsal position the septal necks were situated near the internal margin of the whorls of a coiled shell, hence Ammonoidea which exhibited this feature are referred to the sub-order Intrasiphonata, represented by only one family, the Devonian Clymeniidae (Fig. 181C), which achieved great diversity of shell-form and other characters. All the other ammonites are Extrasiphonata, with septal necks piercing the septa usually near the external or ventral margin of the whorls.

The lines that mark the contacts of the septa with the shell-wall are called septal sutures, and are visible only when the shell is worn thin or dissolved so as to leave a mould of the interior (Figs. 182A, 183A). They are approximately circular in the straight cones, but in coiled shells the circles are distorted, and the septa take on marginal undulations which are traced

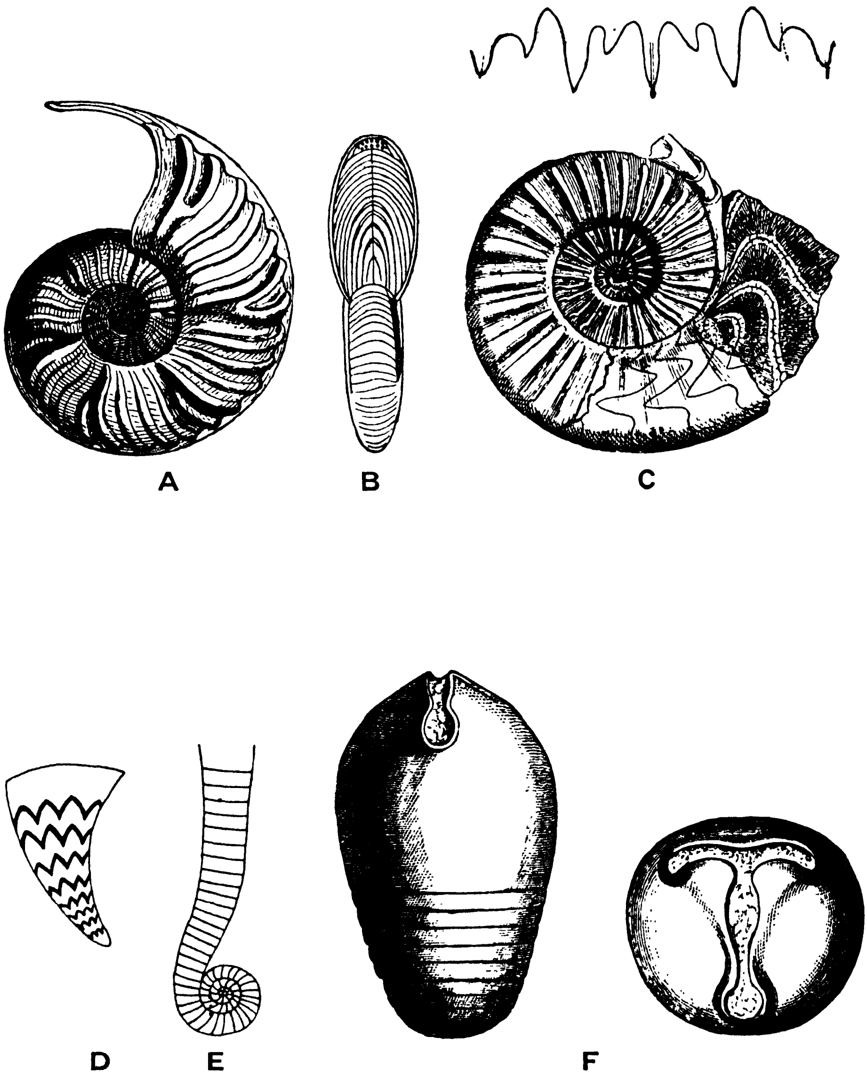


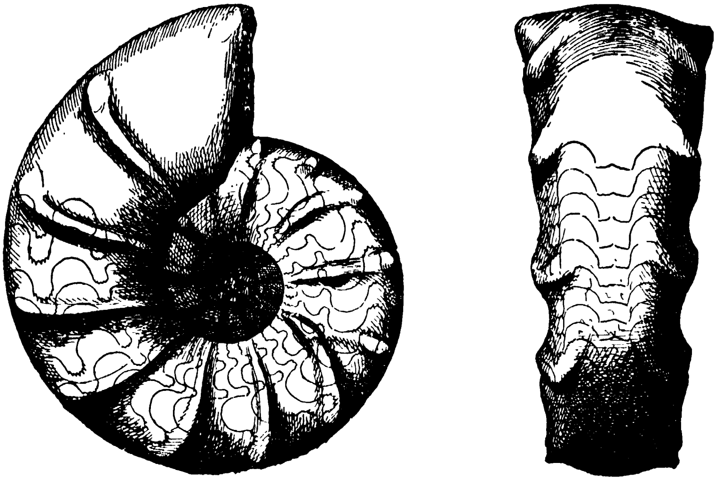
FIG. 181. Ammonoidea A-C, G-I; Nautiloidea D-F.

A. *Schloenbachia.* A Lower Cretaceous ammonite, showing ventral rostrum. (After Zittel.)

B. Apertural view of an ammonite, showing aptychus in position. (After Owen.)

C. *Gonioclymenia,* showing dorsal siphunclar sheath, septa, sutures and shell ornament. (After Zittel.)

D. A cyrtocone, with colour markings. (From Spath, after Ruedemann.)



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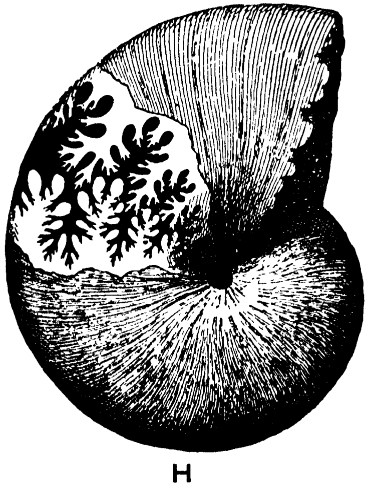

H

I

FIG. 181 (*continued*).

E. *Lituites*, a nautiloid in which the later part of the shell is uncoiled. (From Spath, after Dollo.)

F. *Gomphoceras*, a short orthoconic nautiloid with constricted aperture. (After Zittel.)

G. *Ceratites*. H. *Phylloceras*.

I. *Baculites*, showing early whorls, part of the later uncoiled portion, and simplified sutures. (From Spath, after Dollo.)

by the sutures. In the ammonites this waving or folding of the sutures showed remarkable variety and even complexity of pattern (Figs. 181G and H, 183B), and is of great value in indicating relationship.

NAUTILOIDEA range from Cambrian to present, but have been in decline since Lower Devonian. They are important fossils in Palaeozoic rocks, where the shells are often in the form of a straight cone, like *Orthoceras* (Fig. 182). In addition to orthocones, Palaeozoic rocks yield nautiloids showing various degrees of spiral incoiling, from the slightly curved cyrtocone (Fig. 181D) to the closely coiled nautilicone (Figs. 179, 183). Jurassic and later forms are coiled, and the order is represented from Miocene to Recent only by the genus *Nautilus*. The straight nautiloids, as such, disappeared after the Trias, but were probably represented in later times by the host of Jurassic and Cretaceous belemnites (see below) and their modern dibranchiate descendants. During the Palaeozoic the Nautiloidea also produced a number of forms showing secondary uncoiling of coiled shells (Fig. 181E), helicoid coiling and curiously constricted apertures (Fig. 181F), features that are usually regarded as indicative of racial old age, but may well have been adaptations to particular modes of marine life. The genus *Aturia* which had a comparatively short range from uppermost Cretaceous to its sudden extinction in the Miocene, is analogous to the Clymeniidae in having a dorsal siphuncle.

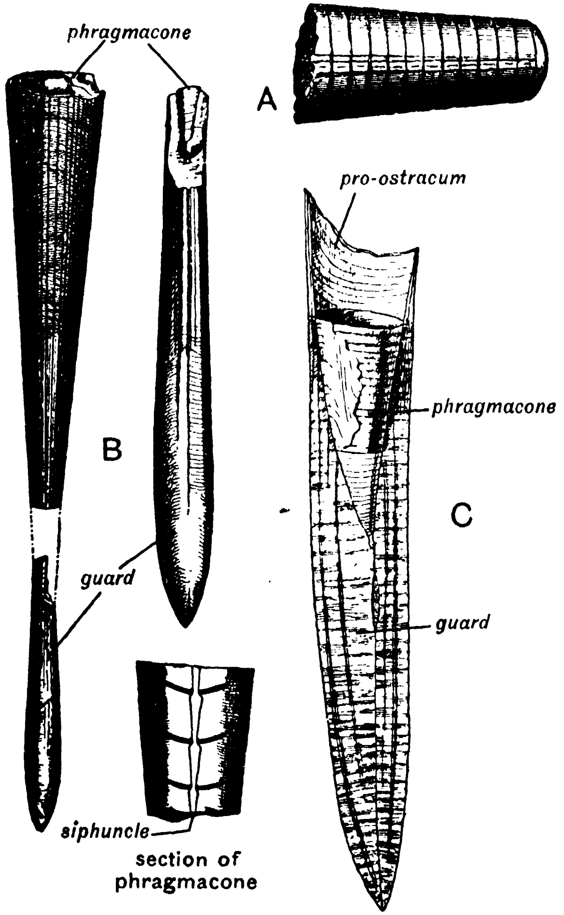

FIG. 182. A. *Orthoceras*. B. *Aulaccoeras*. C. Longitudinal section of belemnite.

The AMMONITES were derived from the nautiloids in the Lower Palaeozoic. Some of the early forms of the Upper Silurian or Lower Devonian were straight (perhaps secondarily) but more or less contemporaneously with these occurred coiled forms that are almost indistinguishable from nautiloids. These early coiled ammonoids are known as goniatites (Fig. 305), from the typical Carboniferous genus *Goniatites.* The siphuncle became stabilized in a ventral position, and the smooth, uncrumpled goniatitic sutures are characterized by more numerous undulations than those of coiled nautiloids, later forms often having pointed lobes (backward undulations) and saddles (forward undulations) or angular lobes and broad lateral saddles. Goniatites are used for zoning the Millstone Grit formation of the British Carboniferous.

In some goniatites of the Permian can be seen the beginnings of the 'crimping' or minute subdivision of the lobes and saddles which characterized the 'ammonitic' type of suture and reached its maximum complexity in the marine Trias (Fig. 183B), when the ammonites were at their acme, and showed astonishing variety of sutural pattern, shell-form, and ornament. This exuberance of variation is reflected in the multiplicity of families and genera which palaeontologists have found necessary for the systematic arrangement of the Triassic ammonites. A characteristic type of suture, in certain stocks of these Triassic ammonites, has denticulate lobes and smooth saddles. It is known as the ceratitic suture, from its typical development in the genus *Ceratites* (Fig. 181G), and its denticulate lobes are obviously derived from the subdivision of pointed lobes of goniatitic type. An interesting reversion to this type of suture is seen in the so-called pseudo-ceratites of the Cretaceous.

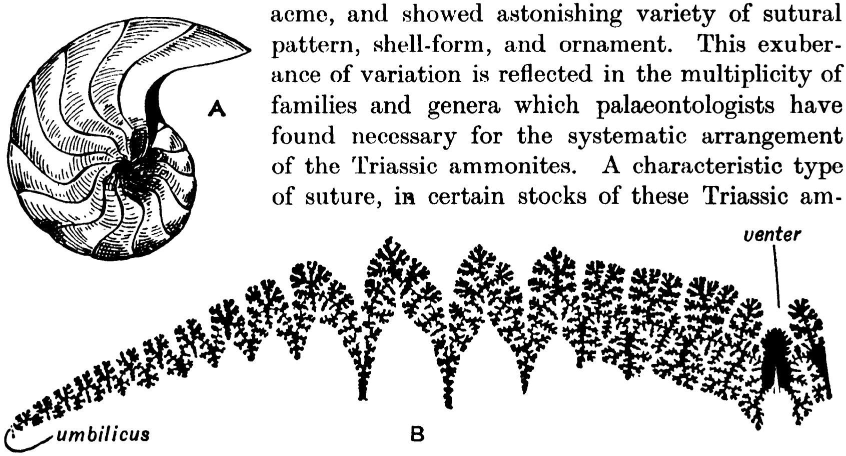

FIG. 183. A. Internal mould of *Nautilus*, showing septal sutures.
B. Suture of *Pinacoceras* (Upper Trias). Only one half is shown from the mid-ventral (peripheral) line to the umbilical margin. (After Hauer.)

Not a single genus of Triassic ammonites and only one family (Phylloceratidae, Fig. 181H) survived into Jurassic, but from this radical the ammonites again expanded into a bewildering number of forms, which are used to zone the Jurassic System, and to a lesser extent the Cretaceous. In the latter system uncoiling and helicoid coiling appeared in certain stocks, often accompanied by simplification of the suture. One family of uncoiled forms, the Baculitidae (Fig. 181I), were dominant towards the end of the Cretaceous, but normal coiled forms persisted and the latest known species before the sudden extinction of the Ammonoidea near the end of the Upper Cretaceous had a suture that rivalled in complexity the acme of sutural specialization in the Upper Trias.

The shell in the COLEOIDEA has lost its external protective function and become a relatively small structure situated dorsally and enveloped in a fold of the mantle to form a rigid axis for the body ; in *Octopus* it is entirely absent. The BELEMNOIDEA appeared in the Trias with the genus *Aulacoceras* (Fig. 182B), which differed from a straight nautiloid like the Palaeozoic *Orthoceras* mainly in having the apex of the conical shell protected by a small, solid calcareous rostrum or guard. This guard was deposited in a fold of the mantle, that is, the shell of *Aulacoceras* was already partially internal. In the later belemnites of the Mesozoic the guard increased and the shell (phragmacone) decreased in size (Fig. 182C), the entire structure having obviously become internal.

The belemnites are numerous in the Jurassic and Cretaceous, and are sparsely represented in Kainozoic rocks and in Recent seas by a few forms that differ considerably from their Mesozoic forerunners.

The LAMELLIBRANCHIA (also called Pelecypoda) are the bivalved Mollusca—oysters, mussels, clams, etc. The valves of the shell, corresponding to two lobes of the mantle, lie on each side of the body (Fig. 184), not dorsal and ventral as in the brachiopods. The head, which is well developed in the gastropods and cephalopods, has degenerated and is quite absent. The main mass of viscera lies in the upper part of the shell. The foot (Figs. 184, 185), typically hatchet-shaped, is situated on the ventral surface of the visceral mass between the mantle lobes, and can be extended beyond the valve margins. Lamellibranchs live by passing a current of water through the mantle cavity, to extract oxygen and also the minute particles of organic matter on which they feed. The current is maintained by cilia on the gills and mantle, and the gills act as a sieve to catch the suspended food particles, which are then passed to the mouth by the action of cilia on the inner surfaces of leaf-like expansions of the integument round the mouth.

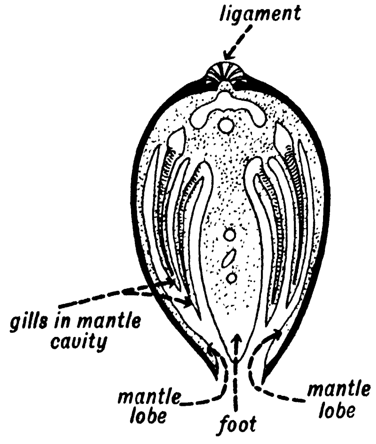

FIG. 184. Cross-section of a lamellibranch showing the general anatomical relationships. Valves in black. (Modified after Schmeil.)

The shell of a normal active lamellibranch, such as a cockle, has equal valves (Figs. 184, 185), each of which is usually asymmetrical about an imaginary line from the beak (umbo) to the opposite or ventral margin; in the bivalve shells of the brachiopods the converse is generally true. The valves of a normal lamellibranch are held together by the two adductor muscles and a dorsally situated ligament (Fig. 186), and are guided in their movement by a system of interlocking ' teeth ' (Fig. 187), that are closely associated with the ligament to form the hinge. In contrast to the brachiopods, the teeth vary greatly in number, and occur on both valves. When present they are of great value in classification, but in fixed and burrowing forms they are usually degenerate or absent. On the inner surface of each valve may be seen the oval scars of the anterior and posterior adductor muscles, which by contraction close the shell (Figs. 186, 189-191). In contrast to the articulate brachiopods, the shell is opened, not by a set of diductor muscles, but by the action of the elastic ligament at the hinge (Figs. 184, 186). The ligament, if external, is under tension when the adductors are contracted, or, if situated internally on the hinge plate, it is under compression; in either case its action is opposed to that of the adductors (Fig. 186). The two adductor scars in each valve are joined by the pallial line, which marks the attachment

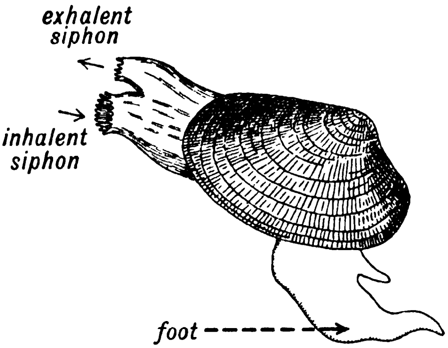

FIG. 185. A lamellibranch showing siphons and foot extended. (After Boas.)

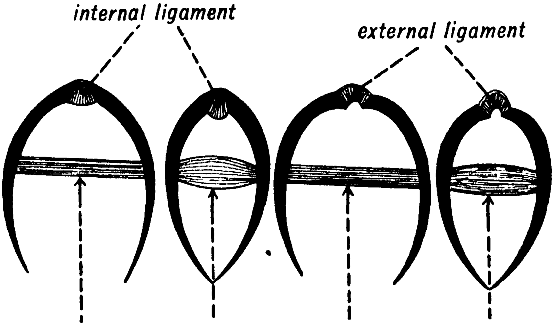

FIG. 186. Diagrams to illustrate action of adductor muscles and ligament. (After Boas.)

of the mantle lobe to the inner surface of the valve and runs near to and parallel with the ventral margin (Fig. 191).

Lamellibranchs have adapted themselves to varied modes of life, with consequent strange modifications of anatomy and shell (Fig. 188). The oyster, *Ostrea*, lies on one valve, which is cemented to the sub-rock, a condition that gives rise to a heavy lamellar growth of the cemented valve ; *Hippurites* (Fig. 319B), an extinct form of the Upper Cretaceous, sessile on one valve in rapidly accumulating muddy sediment, developed coral-like growth and strange deformation of all the shell parts ; the ship-'worm,'

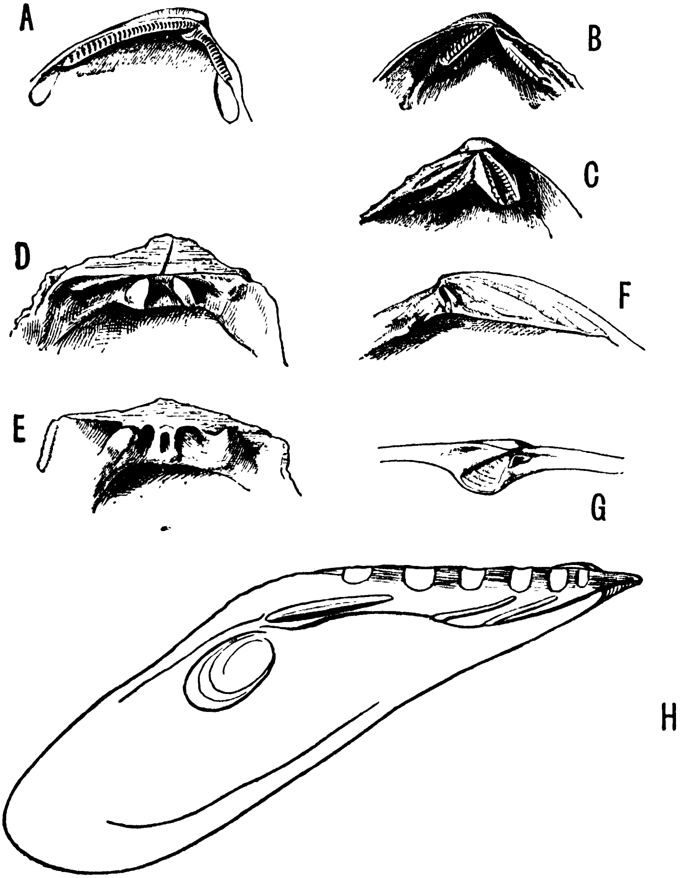

Fig. 187. Hinges of various Lamellibranchia. (After Woods.)

A. *Nucula*. F. *Lucina*.
B and C. *Trigonia* (right and left valves). G. *Lutraria*.
D and E. *Spondylus* (right and left valves). H. *Gervillia*.

Teredo, with its worm-like form and modified shell is adapted for burrowing deeply in wood; the scallop, *Pecten*, swims freely by rapid clapping of the valves; the mussel, *Mytilus*, is attached by a bundle of horny fibres (the byssus) secreted by a gland in the foot.

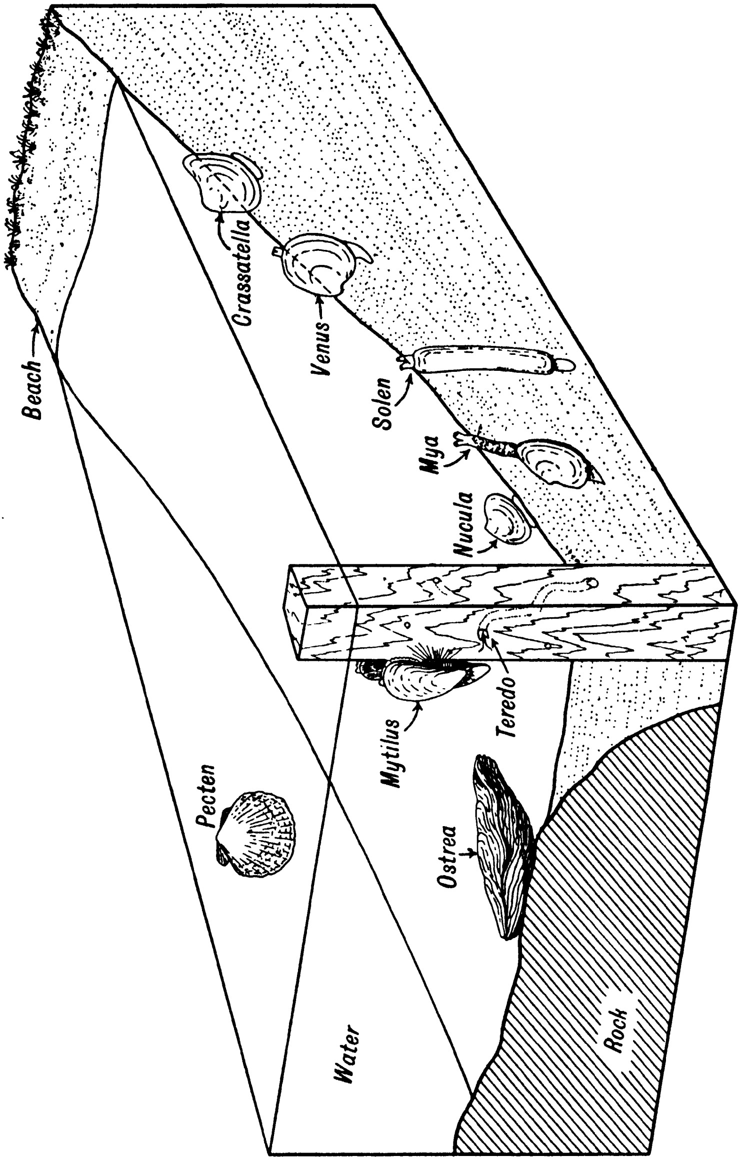

FIG. 188. Block diagram to illustrate adaptation of various lamellibranchs to different environments. (With acknowledgments to Berry and Twenhofel and Schrock.) Not to scale.

In byssal fixation the byssus acts as an anchor. The lamellibranchs which adopt this mode of life are usually exposed to wave or current action, which causes the shell to drag at its anchor. The dragging tends to obstruct the growth of the anterior parts, which remain small and poorly developed. In extreme cases they may not develop at all—the animal is morphologically all posterior. The process of anterior degeneration is expressed in the relations of two lines—the hinge line and the line joining the adductor muscles. These tend to move from a parallel relationship in the normal forms to a perpendicular relationship in the forms where the effects of byssal fixation are extreme. It is also expressed by the relative sizes of the adductor scars in each valve, the anterior adductor muscle becoming smaller and finally entirely atrophied (Fig. 189).

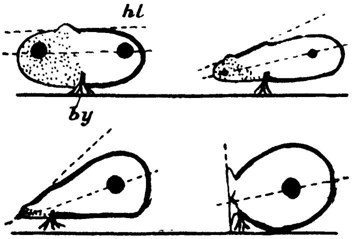

FIG. 189. Diagram to illustrate the effects of byssal fixation on the form, orientation and musculature of lamellibranchs. (After Swinnerton.)

The problem in adaptation to be solved by the mud-burrowing lamellibranchs has been to provide a water supply to the mantle cavity when lying buried in the mud. The solution to the problem has been obtained by uniting the mantle edges at various points and by the extension of the posterior mantle edges to form inhalent and exhalent tubes (siphons). Even in normal forms which do not burrow it is important to prevent stagnation of the water supply in the mantle-cavity, and regular inhalent and exhalent currents are induced in some forms by uniting the mantle edges first at one and then at two points posteriorly, giving two apertures, a dorsal for the exhalent current and a ventral for the inhalent (Fig. 190). In the evolution of mud-burrowing forms it was easy to extend the edges of these two apertures into long retractile siphons (Fig. 185) that reach the surface of the mud.

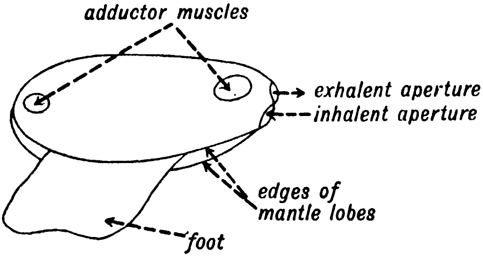

FIG. 190. Diagram of lamellibranch with shell removed to show formation of exhalent and inhalent apertures by union of the mantle edges at two points posteriorly. In some genera the margins of these apertures are produced to form long tubes, the syphons (*cf.* Fig. 185), which may remain separate or may be enclosed in one envelope. (After Boas.)

The muscles for their operation are attached to the inner walls of the valves, and their impressions make a deep bend (pallial sinus) in the pallial line just below the posterior adductor muscle-scar (Fig. 191). The deeper the animal habitually lives in the mud, the longer the siphons, and therefore the bigger the muscles necessary for their operation and the deeper the pallial sinus.

The classification of the Lamellibranchia has been variously based on the adductor muscles, pallial line, gills, and hinge. The first two are unsatisfactory, because the condition of these structures reflects the habits rather than the relationships of the animals. The gills are not available to palaeontologists, and this classification also gives anomalous results. The hinge is a relatively stable structure that affords a good basis for classification, the original form of which has been modified by the French palaeontologist, Douvillé, who recognised a primary adaptive radiation into active, fixed, and burrowing types. This classification is not ecological, because within the primary grouping modifications of the shell that reflect changes of environment can be readily recognised. Unfortunately the scheme was left unfinished by Douvillé, who proposed no names for his primary groups.

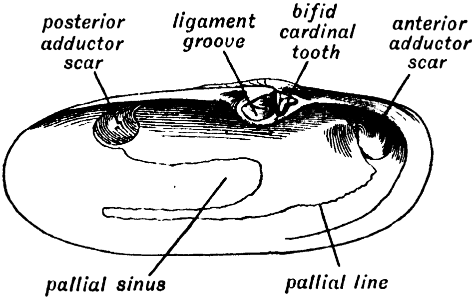

FIG. 191. Interior of left valve of *Lutraria*, a mud-burrowing lamellibranch, showing deep sinus in the pallial line, below the scar of the posterior adductor muscle. (After Zittel.)

Lamellibranchs range from Upper Cambrian, and, like gastropods, are at their acme at the present day. Throughout their geological history they are useful fossils. Both marine and non-marine forms are well represented.

CHAPTER XLIX

CHORDATA

The Chordata have at some period of their development a notochord, or unsegmented elastic rod, situated dorsally to the alimentary tract and ventrally to a dorsal nerve cord. The notochord is the basis of the complex endoskeleton of the higher chordates.

Of four sub-phyla, the Vertebrata are by far the largest and alone have any palaeontological interest, for, unfortunately, the others have left no traces in the rocks. The sub-phylum Vertebrata comprises cyclostomes, fish, amphibia, reptiles, birds and mammals. There is an external skeleton of scales or bony plates in the first three classes, modified to feathers in birds and to hair in mammals. The endoskeleton as a rule is internal although certain endoskeletal structures, like the antlers of deer, may become external during development. The endoskeleton comprises (1) an axial skeleton situated dorsally, and (2) an appendicular skeleton.

(1) In the higher vertebrates the axial skeleton forms a ' back-bone ' or spinal column consisting of a number of separate bones (vertebrae) arranged in a series that articulates at the anterior end to the skull, and passes backward into the tail. The ring-like centre (centrum) of each vertebra (Fig. 192), gives off dorsally two processes which unite above the spinal cord to form the neural arch. A similar pair of processes developed ventrally furnish the haemal arch to protect the ventral blood-vessels. They may surround these vessels in the tail region, uniting below to form a haemal spine (Fig. 192C, D) ; or they may remain unconnected as lower transverse processes. The ribs are originally the cut-off terminations of the enlarged haemal arch in the thoracic region ; in the higher vertebrates the thoracic ribs are united distally to the breast-bone (sternum). The skull includes (*a*) the cranium or brain-case, and (*b*) the jaws and visceral skeleton. The cranium originates as a pair of cartilaginous rods lying on either side of the anterior end of the notochord. From these the cartilage grows upward to surround the brain. In the higher vertebrates cartilage is ultimately replaced by bone. Below the cranium a series of cartilaginous or bony arches surrounds the anterior end of the alimentary canal, forming the visceral head-skeleton. These arches are best seen in their association with the gills of fish (Fig. 193). The first arch of the visceral skeleton forms the jaws. Some craniate chordates

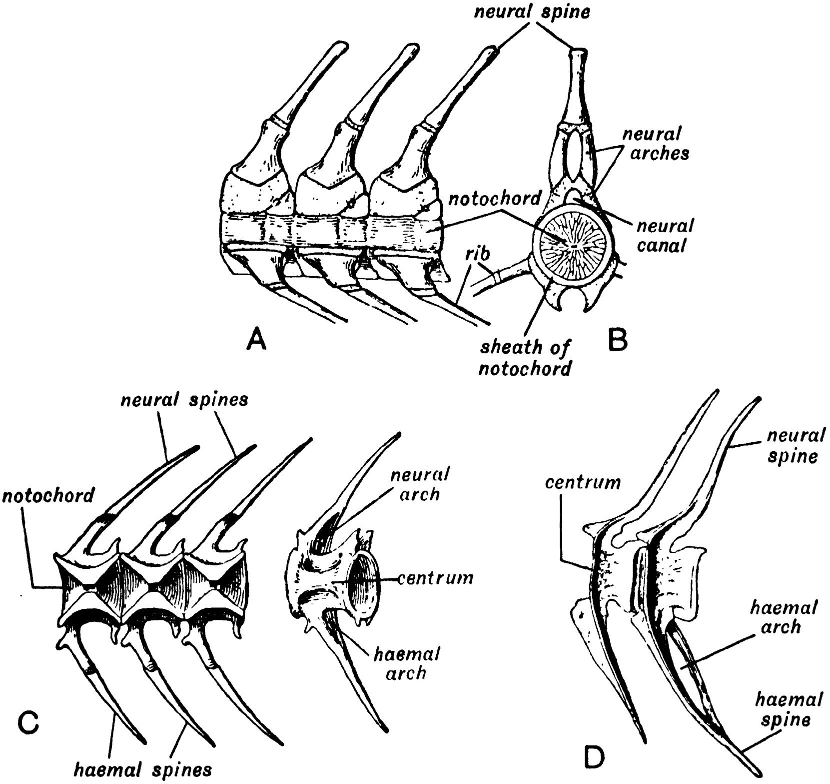

FIG. 192. Vertebrae. (After Zittel-Eastman.)

A and B. Side view and transverse section of abdominal vertebrae of sturgeon, showing unconstricted notochord. Cartilage dotted.

C. Caudal vertebrae of carp. Three in longitudinal section, showing constricted spaces for notochord.

D. Last abdominal and first caudal vertebra of carp.

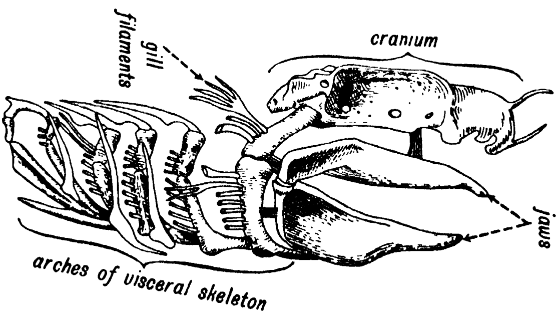

FIG. 193. Cranium and visceral skeleton of a dogfish. Most of the gill-filaments cut short for clearness. (After Reynolds.)

like the lamprey and hagfish have no jaws and are classed as Agnatha or Cyclostomata (Fig. 198). They have eel-like bodies without paired fins and with wholly cartilaginous skeletons.

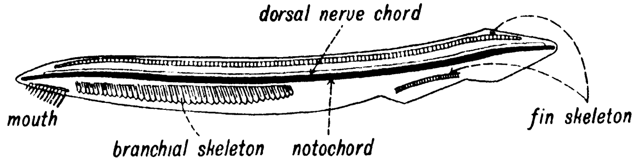

FIG. 194. *Amphioxus*. Diagram of outline and skeleton. Notochord in black. (Modified from drawing in Index. coll. at Brit. Mus.)

(2) The appendicular skeleton comprises a variable number of limb-bones articulated to the limb girdles, in the fore-limbs to the shoulder (pectoral) girdle and in the hind-limbs to the pelvic girdle.

In the development of a young vertebrate the endoskeleton consists at first of only the notochord, a condition found to-day in the adult of the lancelet, *Amphioxus* (sub-phylum CEPHALOCHORDATA, Fig. 194). *Amphioxus* is about 4 inches long and passes a sluggish existence partly buried in sand, where it feeds on micro-organisms. In the subsequent development of the individual vertebrate cartilaginous centra are deposited in the sheath surrounding the notochord, constricting it and causing it to atrophy to a varying extent (Fig. 195). The same process is seen in the evolution of the early fish, the notochord becoming progressively more and more constricted by cartilage which may ultimately be replaced by osseous substance to form bones, called cartilage bones because preformed in cartilage. Some bones of the skull and jaw are not preformed in cartilage, but are developed by the ossification of a membrane. These membrane bones were originally of external origin, but later became intimately related to the endoskeleton.

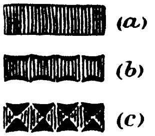

FIG. 195. Diagram to illustrate progressive constriction of notochord by cartilage. (After Swinnerton.)

Nothing is known from fossil evidence regarding the origin of vertebrates, and we only get a few hints from the anatomy and embryology of certain primitive living chordates, like *Amphioxus*. The larva of the modern sea-squirts or Tunicata (sub-phylum UROCHORDATA) has a short notochord in the tail (Fig. 196B), similar to that of *Amphioxus*. In development the larva of the tunicate settles down to a sedentary life, loses tail, notochord and dorsal nerve-chord, and becomes strangely deformed (Fig. 196A). A still more primitive organization of chordate type is seen in the worm-like creature *Balanoglossus* (sub-phylum HEMICHORDATA), which varies in length up to about 6 feet and burrows in sand and mud (Fig. 197). There is a well-

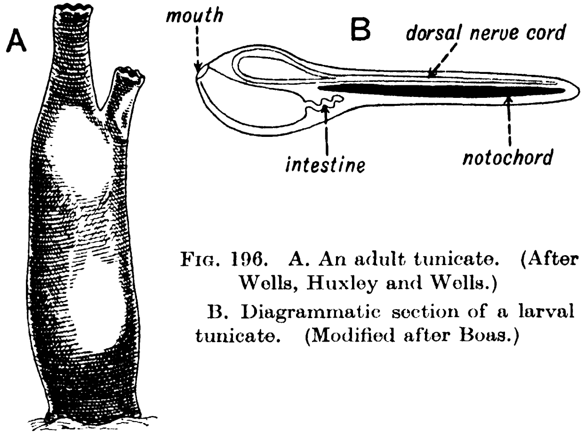

FIG. 196. A. An adult tunicate. (After Wells, Huxley and Wells.)
B. Diagrammatic section of a larval tunicate. (Modified after Boas.)

defined head, forming a burrowing proboscis, rudiments of gills and chitinous skeleton bars, dorsal nerve cord and ventral alimentary tract. This is the fundamental architectural plan of the chordate organization, but it lacks a notochord, except perhaps a small structure that grows forward from the alimentary canal into the proboscis with the typical microscopic structure of a notochord. The hypothetical first stage of vertebrate evolution, doubtless similar in organization to these primitive chordates, is unrepresented by fossils, owing to the perishable nature of the notochord and the absence of other hard parts.

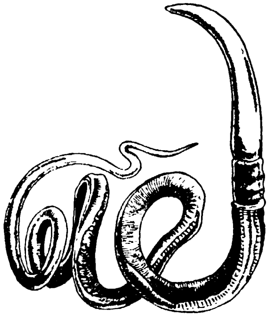

FIG. 197. *Balanoglossus.* (After Wells, Huxley and Wells.)

The second stage, introducing the sub-phylum VERTEBRATA, may be called the CYCLOSTOME STAGE, the general organization corresponding to that of living cyclostomes, the lampreys and hagfishes (Fig. 198). This stage is well represented by fossils in the Upper Silurian and Devonian, and probably

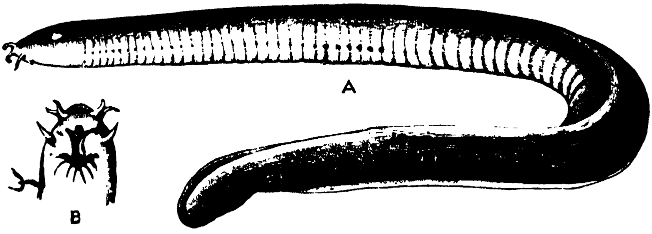

FIG. 198. Hagfish, *Myxine glutinosa.* (After Cambridge Nat. Hist.) A, lateral view ; B, ventral surface of head with mouth and tentacles.

flourished in the Ordovician too. Fragments of armour, the oldest fish fossils of which we have knowledge, have been found in the Ordovician of Colorado and other parts of western North America. The early near-cyclostomes have highly developed body armour and are known collectively as Ostracodermi. They comprised two groups with very different modes of life—freely swimming forms with fusiform streamlined bodies, and others with depressed flattened bodies adapted to a grovelling life on the sea-floor. The former (order Anaspida, Fig. 199) did not exceed a length of about 10 centimetres. They carried a single nostril opening on the top of the head, and also an oblique row of perforations on each side of the same, suggesting gills situated in separate pouches. Both these characters are found in the lampreys and distinguish them from the true fishes. Further the tail was hypocercal (*i.e.* the spinal column went into the lower lobe) exactly as in the larva of the modern lamprey, a condition unknown in the higher fishes, but recurring in the ichthyosaurs, marine reptiles of the Jurassic (see p. 330). There are traces of paired fins, and the arrangement of scales round the mouth suggests that the jaws were not so degenerate as in the lamprey. The modern cyclostomes with their eel-shaped bodies and absence of paired fins and jaws are mere relics that give little idea of their stock in its prime.

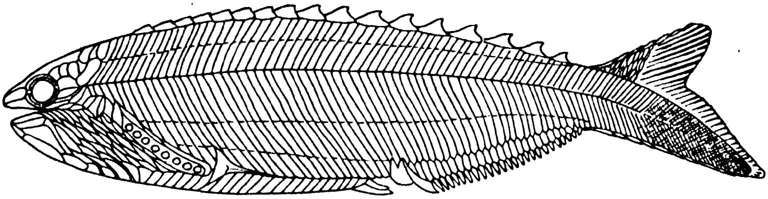

FIG. 199. *Pterolepis*, an anaspid ostracoderm. (After Kiaer.)

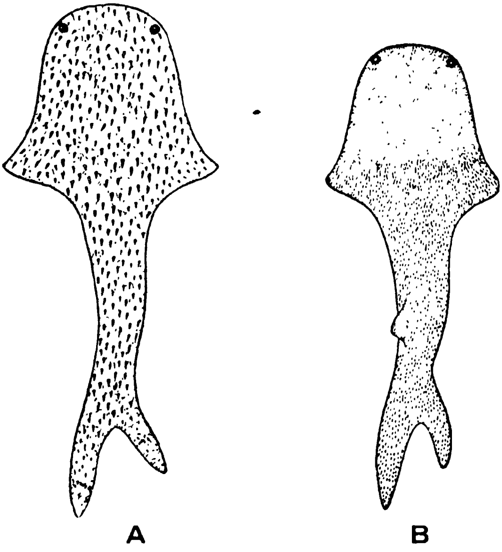

FIG. 200. A. *Lanarkia*. B. *Thelodus*. (After Traquair.)

The bottom-dwelling ostracoderms comprise two orders and yield a large number of characteristic fossils in the Upper Silurian and Old Red Sandstone.

In primitive forms like *Lanarkia* and *Thelodus* (Fig. 200) of the Downtonian, the exoskeleton consisted of dermal tubercles like the shagreen of the shark. In the later forms a process of fusion converted the tubercles into an armature of bony plates, as in the rostrate *Pteraspis* (Fig. 201) of the Downtonian and Lower Devonian, and the Cephalaspidae (Fig. 202 A-C) of the Upper Silurian and Devonian. The latter with their rigid and characteristically rounded head-shield, paired pectoral fins, lateral fin-folds in the pelvic region, and heterocercal tail are the best-known of all ostracoderms. In *Cephalaspis* and most other genera, but not in *Hemicyclaspis*, the pectoral

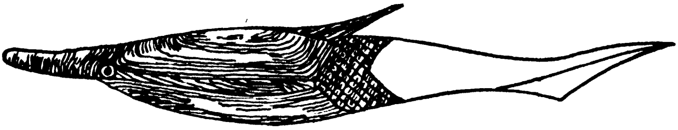

FIG. 201. *Pteraspis*. (After Smith Woodward.)

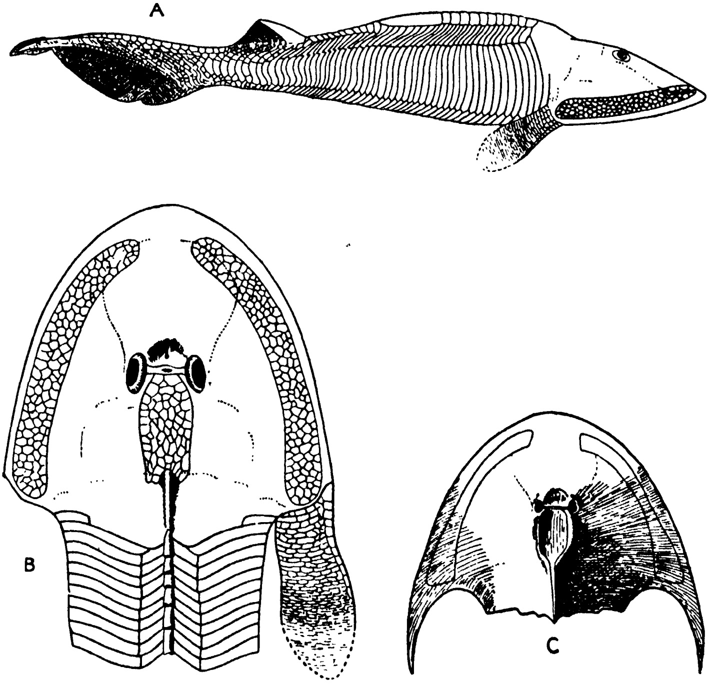

FIG. 202. Representative Cephalaspidae. (After Stensiö.)

A. *Hemicyclaspis*. Lateral view.
B. Ditto. Dorsal view of head-shield.
C. *Cephalaspis*. Dorsal view of head-shield.

angles of the head-shield were produced into short horns (cornua). Many specimens from Spitsbergen and Britain in wonderful preservation have been dissected by Professor E. A. Stensiö of Stockholm, and have revealed the complex anatomy of the head in extraordinary detail. Stensiö's investigations, confirming earlier studies on Norwegian Anaspida, show that the ostracoderms had close affinities with the modern degenerate cyclostomes.

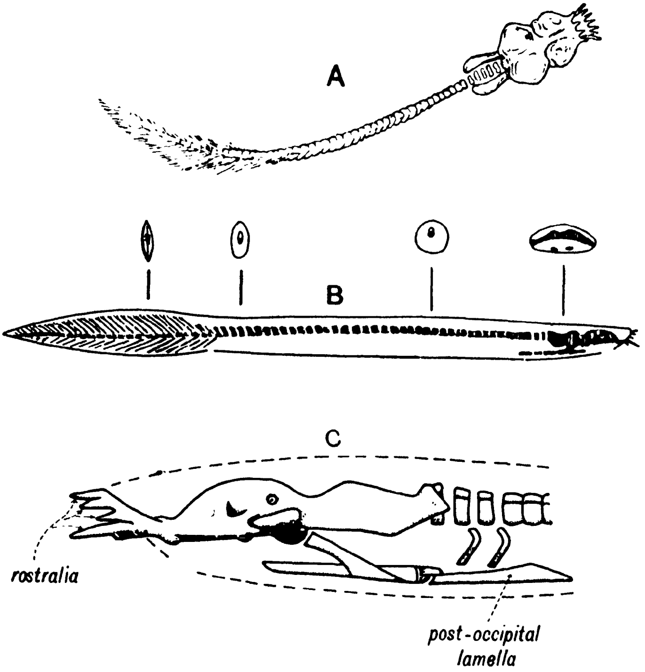

FIG. 203. *Palaeospondylus gunni* Traquair, length 1 inch.
A. Dorsal view of skeleton. (After Traquair.)
B. Lateral view. (After Bulman.)
C. Lateral view of head. (After Bulman.)

Before leaving the discussion of Palaeozoic cyclostome-like forms, reference must be made to the curious *Palaeospondylus* (Fig. 203) from the Middle Old Red Sandstone of Caithness. This little creature had a maximum length of about 5 centimetres. The skull was flattened and terminated anteriorly by a ring of slender processes or rostralia. Projecting backward from beneath the skull and originating in paired rods that have been interpreted as part of a visceral head-skeleton, there was a pair of stout processes (post-occipital lamellae). The latest view regarding the nature of these ventral head-structures is that they correspond to the segmented basal cartilage which gives attachment to the rasping ' tongue ' in hagfishes. The cylindrical middle region of the body passed backward into the compressed tail-fin. The skeleton was well calcified, with ring-like vertebral centra surrounding the unconstricted notochord. The centra bore neural spines but no ribs. In the caudal region neural and haemal spines became elongated to support a tail fin. There have been many suggestions regarding the affinities of *Palaeospondylus*, but the most recent work places it almost without doubt among the cyclostomes. It differed from the modern specialized and degenerate members of that group in having the endoskeleton well calcified, with distinct vertebrae surrounding the notochord.

The stages that succeeded the cyclostomatous phase of vertebrate evolution may be conveniently discussed in a succession of chapters devoted to the five remaining vertebrate classes.

CHAPTER L

CHORDATA : CLASS PISCES

Fishes (in the strict sense, *i.e.* excluding cyclostomes and ostracoderms) are aquatic vertebrates with jaws and paired fins. There is no movable neck, and except in the case of special adaptation, the body is more or less streamlined to minimise the friction of the surrounding water. Respiration is performed by gills, delicate hollow filaments in which blood circulates. They are supported by the cartilaginous or bony gill-arches of the visceral head-skeleton (Fig. 193, and p. 307), and are sometimes protected externally by a bony operculum. Water is taken in through the mouth and passed out over the gills, where the blood extracts free oxygen dissolved in the water. A hydrostatic organ, the air-bladder, is present in the higher fishes. In its primitive condition it forms a lung in certain genera that breathe air (see p. 318). The skin of fishes is usually protected by scales, spines, or bony plates.

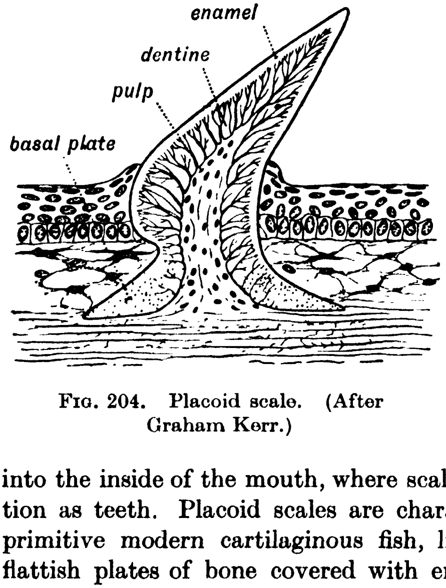

Fig. 204. Placoid scale. (After Graham Kerr.)

There are three main types of scale : placoid, ganoid and cycloid. Placoid scales (Fig. 204) are like teeth in shape and structure. In fact, teeth are simply modified placoid scales. In the sharks, for example, the skin passes over the jaw into the inside of the mouth, where scales that cover it are enlarged to function as teeth. Placoid scales are characteristic of the earliest fish and of primitive modern cartilaginous fish, like the sharks. Ganoid scales are flattish plates of bone covered with enamel ; they are of various shapes, rhomboidal and circular. Detached ganoid scales are often preserved as fossils. Cycloid scales characterize modern fish with fully ossified skeletons ; they are extremely thin plates of bone, usually circular and over-lapping.

The principal organ of locomotion is the powerful tail. There are three main types of tail (Fig. 205)—(1) Diphycercal (vertebral column disposed symmetrically within a single pointed fin lobe); (2) Heterocercal (asymmetrical—the vertebral column turns into the upper lobe of the bilobate tail fin; the converse, or hypocercal, condition, as we have seen, was present in some of the early ostracoderms); (3) Homocercal (two symmetrical lobes to the tail fin; the vertebral column again turns up, but ends abruptly and the fin rays are so disposed that the tail fin is symmetrical).

The paired fins are used for steering, and unpaired median fins act as balancing organs. All the fins are supported by skeletal bars, the fin rays. The skeleton may be cartilaginous throughout, but it is usually more or less bony. The limbs of the land-dwelling vertebrates were evolved from the paired fins of fish, but regarding the origin of these fins there is less certainty. The view most widely held is that they originated as continuous folds of skin running along either side of the body and supported by fin-rays. These folds are supposed ultimately to have developed fin-like enlargements at their extremities in the pectoral and pelvic regions while becoming suppressed in the middle region of the body. In the cephalaspids such continuous ventro-lateral fin-folds extend from the pectoral fins to the caudal fin (Fig. 202A), the anterior portion presumably having enlarged to form the paddle-like pectoral fins, while the posterior part remained unchanged.

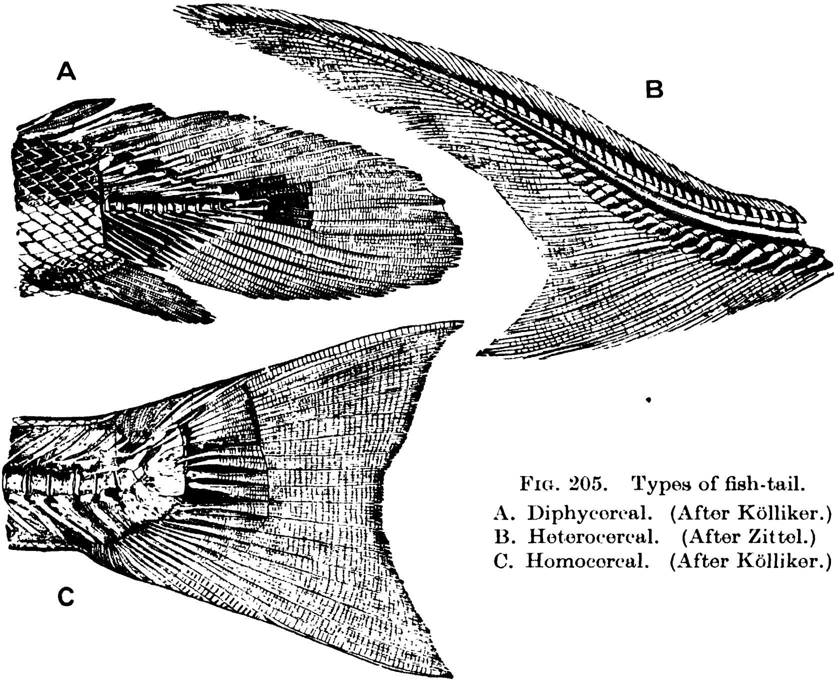

FIG. 205. Types of fish-tail.
A. Diphycercal. (After Kölliker.)
B. Heterocercal. (After Zittel.)
C. Homocercal. (After Kölliker.)

The most primitive of the true fishes, the CARTILAGINOUS FISH, which include the modern sharks and skates, represent the stage in vertebrate evolution that succeeded the cyclostomes. The sharks have a heterocercal tail, mouth on the under surface, and an exoskeleton of placoid scales, which may pass into the mouth and become enlarged to form rending teeth. In shell-fish eaters the teeth in the inner parts of the mouth may fuse to form crushing teeth with flat or spirally grooved surfaces. Sharks' teeth are common fossils.

It is now known that the Palaeozoic forerunners of the sharks, the earliest known true fishes with paired fins, had a large amount of bone in the skeleton, which explains why the cartilaginous stage of vertebrate evolution was for long not recognised as dominant at the appropriate time in the geological record. These earliest 'cartilaginous' fishes (Acanthodii, or spiny-sharks) appeared in the Upper Silurian and ranged throughout the Upper Palaeozoic. The bodies of the Acanthodii had the spindle-shape typical of free-swimming fish, heterocercal tail, partly ossified skull and other calcifications, and a more complicated dermal armour than the modern sharks. All their fins except the tail-fin had strong anterior spines, which, detached, are common fossils. A representative genus was *Climatius* (Lower Old Red Sandstone), in which a row of free spines on each side extended between the pectoral and the pelvic fins (Fig. 206).

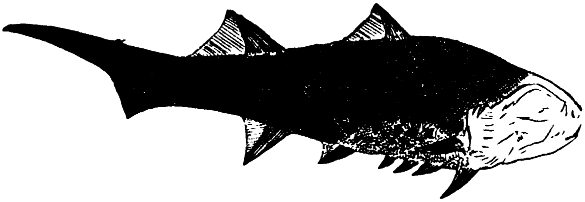

FIG. 206. *Climatius*. (After Powrie.)

The cartilaginous fishes in their prime gave rise, not only to the free-swimming spiny sharks, but also to a bottom-dwelling group, the Arthrodira. In these a heavily armoured head was movably hinged to the armour of the body, and to some extent bone occurred in the endoskeleton. With their heavily armoured anterior region the Arthrodira resembled superficially the Ostracodermi, but they differed in the possession of jaws, paired fins and articulated head. A representative genus was *Coccosteus* (Fig. 295A) of the Middle Old Red Sandstone of Scotland and Devonian generally. In America some very large forms have been found, *Titanichthys* measuring nearly two metres across the head-shield. With the Arthrodira Stensiö associates the order Antiarchi, armoured fishes formerly grouped with the ostracoderms, and comprising among others the stratigraphically important genera *Pterichthys* (Middle Old Red Sandstone of Scotland, Fig. 295B) and *Bothriolepis* (Marine Upper Devonian and Upper Old Red Sandstone). These were characterized by paddle-like appendages in the pectoral region, well developed jaws, symmetrically arranged plates on the head region, and heterocercal tail. The paired pectoral appendages were true fins, with endoskeleton as well as exoskeleton. A transverse articulation of the latter near the middle of each fin gives the limb a superficial resemblance to a jointed crustacean or

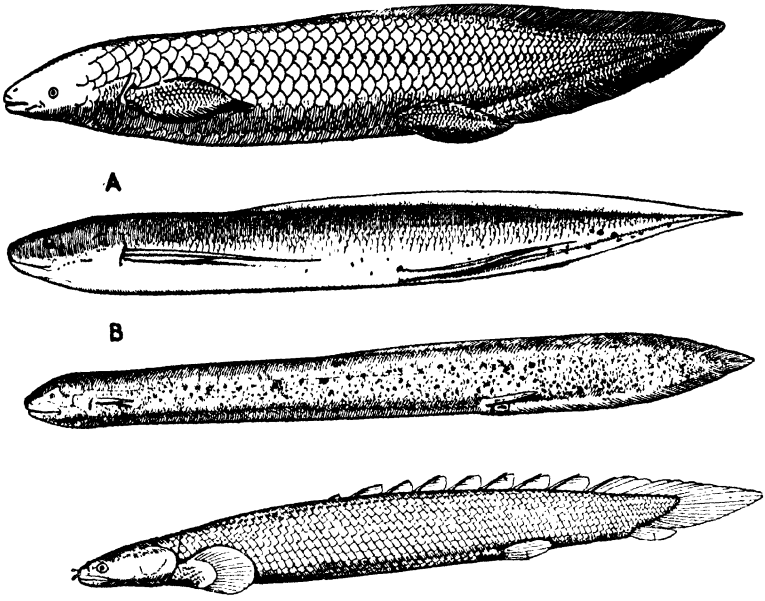

FIG. 207. Modern lung-fish. (After A. K. Maxwell in Graham Kerr.)
A-C. Dipnoi, *Ceratodus*, *Protopterus* and *Lepidosiren*.
D. Crossopterygian ganoid, *Polypterus*.

eurypteridean appendage. *Bothriolepis* had longer paddles than *Pterichthys* and the naked tail had two dorsal fins and a much elongated caudal fin.

Fossils of Elasmobranchii (cartilaginous fishes) other than Acanthodii are common in the Upper Palaeozoic, and the sharks (Selachii) range from Devonian or Lower Carboniferous to the present.

The next advance in the evolution of the vertebrates probably represented the adaptation of some unknown branch of the cartilaginous fish to lacustrine life, but no fossils have been found to link the acanthodian elasmobranchs to the Palaeozoic LUNG-FISH, the earliest representatives of which are found in fresh-water deposits. The lung-fish were the immediate ancestors of the modern fish with bony skeletons and of the terrestrial vertebrates. Characteristically the paired fins are paddles, each having an internal cartilaginous axis. They are represented at the present day by two orders: the Crossopterygii, with two genera of African river fish, *Polypterus* and *Calamoichthys*,* and the Dipnoi with three genera—*Lepidosiren*, South America; *Protopterus*, East Africa; and *Ceratodus*, Australia (Fig. 207).

The air-bladder or swim-bladder that occurs in modern lung-fishes is a hydrostatic organ which adjusts the specific gravity of the body to various depths of water. In the young *Lepidosiren* and *Protopterus* it occurs in its primitive condition as a bi-lobed structure opening ventrally from the anterior region of the alimentary canal (Fig. 208A). The two lobes correspond exactly to the right and left lungs of terrestrial vertebrates, and are used for respiration when special conditions inhibit the use of the well-developed gills. When the waters have dried up *Lepidosiren* and *Protopterus* burrow in mud

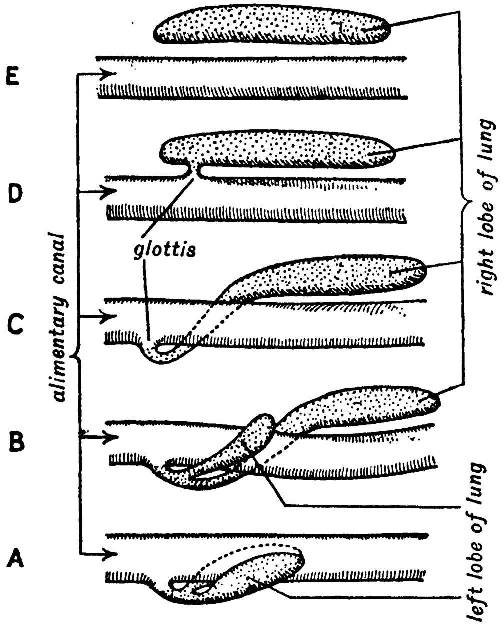

FIG. 208. Diagrams to illustrate evolution of the lung in fishes. (After Graham Kerr.)

A. Primitive symmetrical arrangement of the two lobes.

B. *Polypterus*; left lobe reduced, right lobe has taken up a median position dorsal to alimentary canal.

C. *Ceratodus*; left lobe has disappeared.

D and E. Teleostei; in D the glottis has moved into a dorsal position, and in E the right lobe has lost connexion with the alimentary canal.

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* A single living specimen of a marine crossopterygian, *Latimeria*, has recently been dredged off the coast of Durban, E. Africa. It belongs to a family previously thought to have been extinct since Upper Cretaceous times.

and lead a vegetative existence, breathing air by means of their lungs. *Ceratodus* uses its lung for breathing air in the dry season when the pools are foul with decaying vegetation and the water is useless for gill-breathing. In *Polypterus*, which rises to the surface of the water to breathe air and would drown if kept under, the left lobe is retarded during growth, so that in the adult the right lobe is more than twice as long as the left and takes up a position dorsal to the alimentary canal (Fig. 208B). In *Ceratodus* the left lobe has disappeared entirely, the distal part of the right lobe being dorsally situated (Fig. 208C), as in *Polypterus*. In certain primitive bony fishes the proximal part of the right lobe and its connection with the alimentary canal have shifted to a dorsal position (Fig. 208D), and finally, in the more advanced forms, connection with the alimentary canal is severed (Fig. 208E), and the function of the now dorsally situated air-bladder is solely hydrostatic, having lost the additional respiratory function.

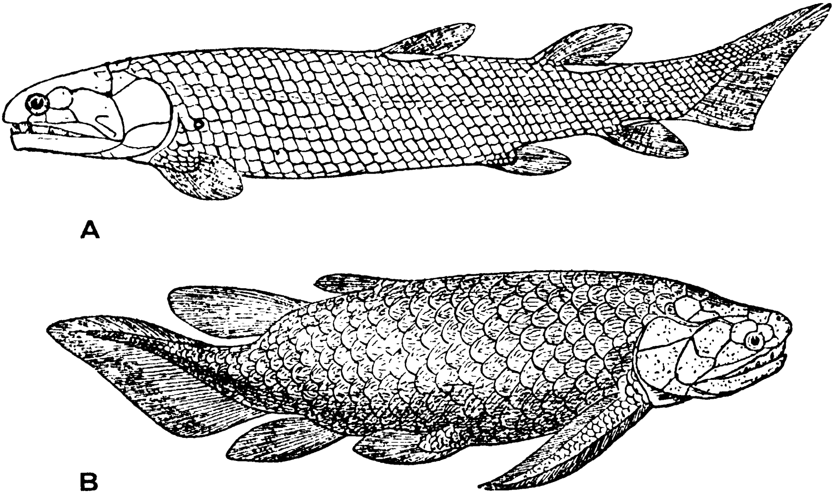

Fig. 209. Devonian Crossopterygii. (After Traquair.)
A. *Osteolepis*. B. *Holoptychius*.

Perhaps the best-known fossil dipnoan is *Dipterus* (Middle Old Red Sandstone of Scotland, Middle and Upper Devonian of Europe and America) with almost rhombic scales, small jaws, acutely pointed fins and numerous small bones on the roof of the skull (Fig. 295C). The Dipnoi were at their acme during the Devonian and have declined since. The genus *Ceratodus* is represented by several species from Trias to the present day, but of the other two living genera only *Protopterus* is represented by fossils (in Oligocene and Lower Miocene of East Africa, approximately its present habitat).

The CROSSOPTERYGII have numerous fossil representatives. *Osteolepis* of the Scottish Middle Old Red Sandstone had a slender body with rhombic scales and short, obtuse lobe-fins (Fig. 209A). A point of special interest in *Osteolepis* was the presence of a pineal foramen in the top of the skull, a feature that became important in the early terrestrial vertebrates (see p. 335 and Fig. 217). Another member of the same family, *Megalichthys*, which yields frequent fossils in the Carboniferous and Permian, had no pineal foramen. *Holoptychius* (Marine Devonian and Middle and Upper Old Red Sandstone) the sole genus of another family, had large ganoid scales of cycloidal form, a short rotund body and acutely lobate pectoral fins (Fig. 209B).

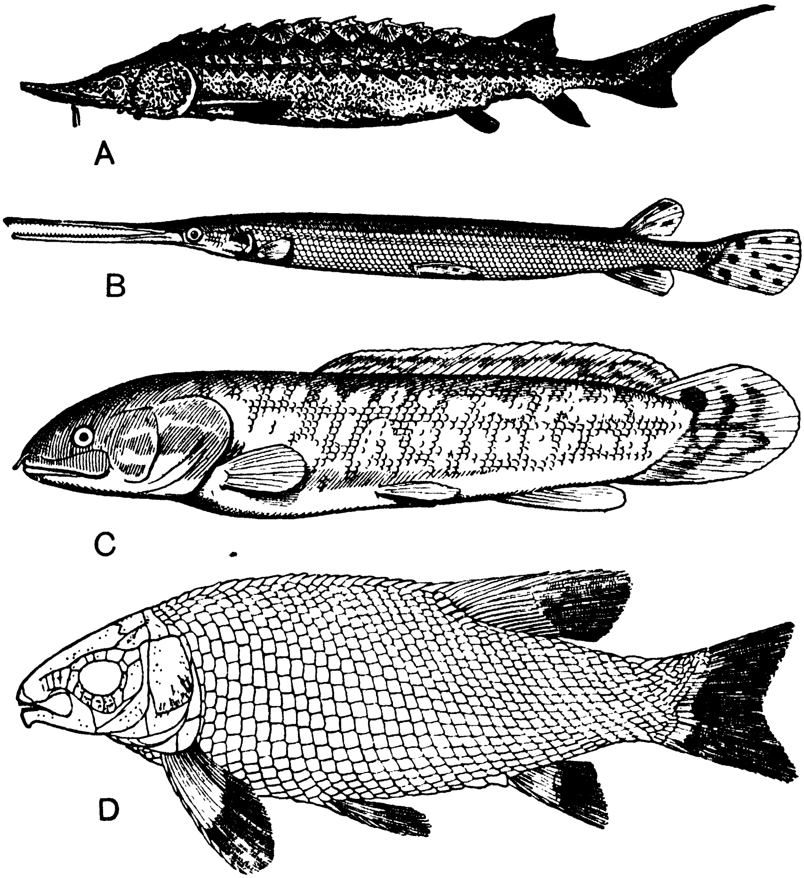

FIG. 210. Actinopterygian ganoids. A-C. Recent. D. Jurassic.
A. Sturgeon, *Acinpenser*. (After Bashford Dean.)
B. Garpike, *Lepidosteus*. (After Maxwell in Graham Kerr.)
C. Bowfin, *Amia*. (After Maxwell.)
D. *Lepidotus*. (After Smith Woodward.)

The lobe-finned ganoids (as the Crossopterygii are sometimes called) declined in numbers during the Upper Palaeozoic, their place being taken by ganoids in which the fins had basal endoskeletal supports instead of a cartilaginous axis, and the relatively large fin-membranes were supported by long dermal fin-rays (*cf.* Fig. 210B). These flourished during the earlier part of the Mesozoic, in fact the Middle and Upper Jurassic might be called the age of ACTINOPTERYGIAN GANOIDS (Fig. 210D), but in the Lower Cretaceous they began to be displaced by the modern bony fish (TELEOSTEI) and are represented at the present day only by such fresh-water fish as the sturgeon and garpike and bowfin (Fig. 210 A-C). The Teleostei developed rapidly during the Cretaceous and are the dominant fish of the Kainozoic. They were derived from actinopterygian ganoids, and are characterized by cycloid scales, homocercal tail, and ossified skeleton. In the higher forms the air bladder loses connection with the gullet.

CHAPTER LI

CHORDATA: CLASS AMPHIBIA

THE teleost fishes are an off-shoot from the main trend of evolution that led to the terrestrial vertebrates. To understand the origin of these latter we have to revert to the lung-fish and especially to the crossopterygian ganoids of the marine Devonian and the Old Red Sandstone, and consider them in relation to the circumstances that led to colonization of the land. Continental conditions had largely supervened at this time and increasing dryness of the climate would tend to reduce bodies of water that had been shut off from the sea. As these became overcrowded and ever more foul and saline, fish that could breathe air by means of an air-bladder had the best chance of survival. A further advantage was conferred on those lung-fish that could use fins with internal cartilaginous axis to leave the overcrowded waters and sprawl over the adjacent land surface in search of food, provided by the plants and plant-feeding invertebrates which colonized the land about this

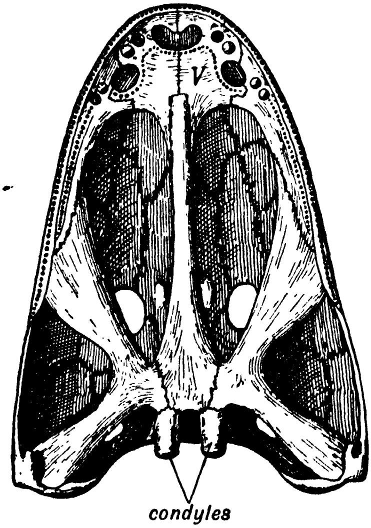

FIG. 211. Skull of a stegocephalian, *Cyclotosaurus*, from below, showing the occipital condyles. (After Fraas.)

time. In fact, the earliest fossil land vertebrates and certain Crossopterygii, such as *Megalichthys*, show so close a correspondence in their skulls that there can be no doubt of their close affinity to a common ancestor.

The migration to land during Devonian times was a stimulus to the evolutionary progress of the vertebrates. It took place under conditions of adversity greater than any that could occur in the uniform environment of the open sea with its abundant supplies of food and oxygen, and its achievement resulted in the rapid development of intelligence that enabled the animals to adapt themselves to the changing condition on land.

One of the earliest requirements of the migrants would be a more useful type of limb than the lobed fin of the first venturesome lung-fish. So long as the habitat was

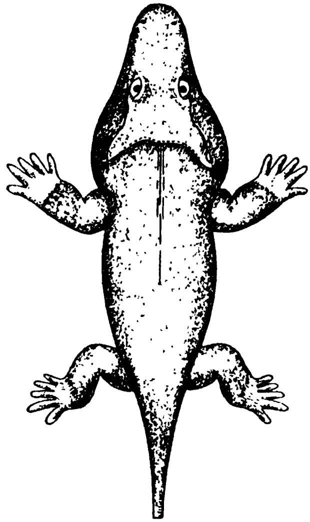

FIG. 212. *Trematops*, a stegocephalian. (After Williston.)

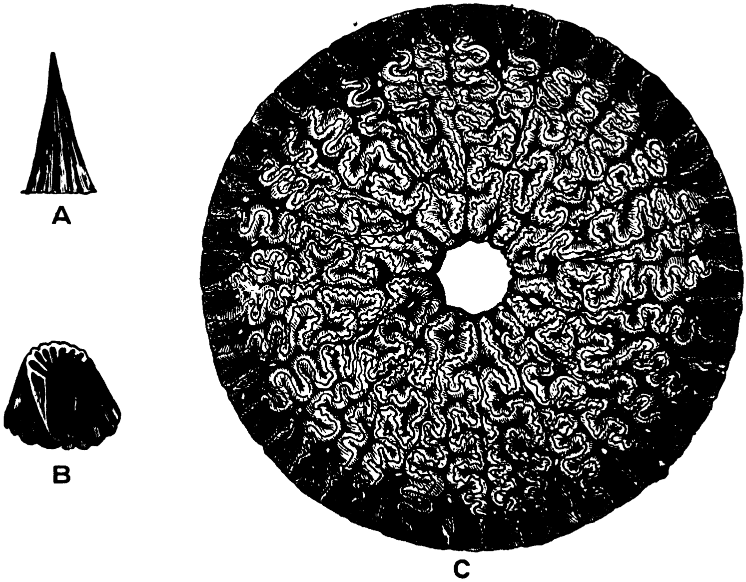

FIG. 213. Teeth of Stegocephalia.

A and B. *Archegosaurus*: A, outer surface. B, sectioned to show folded dentine. (After Zittel.)

C. *Mastodonsaurus*. Sectioned to show labyrinthine structure.

confined to the verges of inland waters this would be achieved by the flattening and digitation of the fin extremities. Downward rotation of the extremities would be the next stage, to lift the body temporarily or permanently clear of the ground, giving the animal a waddling gait. As the vertebrate stock became further emancipated from the neighbourhood of water, a still greater efficiency was achieved by the development of the characteristic double flexure and the swinging of the whole limb from the shoulder and hip articulations in a plane parallel to the body. This condition was attained by the reptiles. Further specialization for speed in the form of digitigrade and bipedal gait characterized several independent stocks of both reptiles and mammals. The lifting of the fore-limbs from the ground in bipedal stocks was a necessary preliminary to their modification as organs of flight (see pp. 336, 337, 342).

The first land-dwelling vertebrates were necessarily limited to the neighbourhood of water, to which they had to return periodically for egg-laying, like their modern non-progressive descendants, the frogs and toads, etc., as eggs would not yet have acquired the tough skin or calcareous shell necessary for hatching on land. That is, these early land vertebrates would be amphibia, passing their early developmental stages in water while acquiring the organs and structures necessary for life on land.

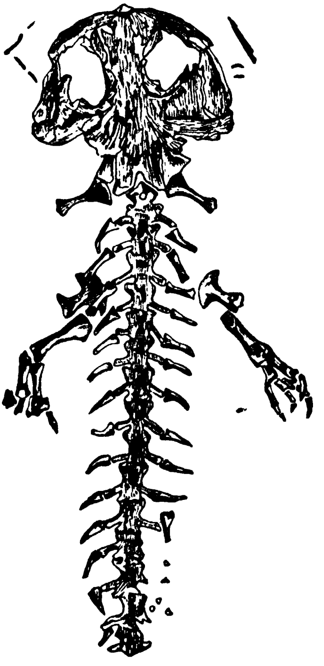

FIG. 214. *Andrias*, "Homo diluvii testis." (After Zittel.)

Some modern amphibia, such as newts and salamanders, have tails, and have a superficial resemblance to certain lizards; others are snake-like, others again, the frogs and toads, are tail-less. They have moist, slimy skins like fish, but most modern forms are without scales. They are cold-blooded and have two processes (occipital condyles, Fig. 211) uniting the skull to the vertebral column. The Palaeozoic amphibia, classed as Stegocephalia, differed considerably from the insignificant amphibia of the present, and dominated the lands of the Carboniferous and Permian. They varied in external form and habits, but all had tails (Fig. 212) and some of them attained considerable size. The skull was roofed by thick dermal bones, and other parts of the body carried armour. The limbs were well developed and resembled those of living tailed amphibia, with four digits to the hand and five to the foot. A pineal eye was present. The teeth were either smooth hollow cones or were vertically grooved on the lower part of the external surface, with corresponding radial infoldings of dentine (*cf.* Fig. 213 A and B) in the pulp cavity. Complication of these dentine structures and interfolding with cement gave the so-called labyrinthodont structure that almost obliterated the pulp cavity (Fig. 213C) and in its extreme development characterized the Triassic Stegocephalia of the order Labyrinthodontia.

Fossil remains of other amphibia are rare, but mention may be made of the Miocene salamander *Andrias scheuchzeri* (Fig. 214), which attained a length of about a metre and has a special historical and literary interest. It was originally described by Scheuchzer in the eighteenth century as *Homo diluvii testis*—' the bony skeleton of one of those infamous men whose sins brought upon the world the dire misfortune of the deluge '. Recently this fossil, which is still preserved at Haarlem, has been the inspiration of a satirical fantasy by a well-known European writer.

CHAPTER LII

CHORDATA : CLASS REPTILIA

Some of the Stegocephalia must have emancipated themselves from the necessity of living in the immediate vicinity of water, for the fossil skeletons of the early reptiles are so similar to those of the Stegocephalia that, without doubt, the one stage evolved from the other. In fact it is almost impossible to discriminate the two stages by means of the skeleton. For example, the Amphibia have typically two occipital condyles uniting the skull to the vertebral column and the Reptilia have one. It is now known that the earliest Stegocephalia had only one condyle like the reptiles to which they gave rise.

The notable development of the more highly organized reptiles may have occurred in response to desert conditions, widespread in the Permian and Trias, and it marked another stage in the adaptation of vertebrates to life on land. Except those specially and secondarily adapted for life in water, reptiles are essentially land animals, breathing by lungs throughout life. Reptiles lay eggs on land to develop in the sun. The eggs are therefore modified. They are large, like birds' eggs, with a tough parchment-like skin or calcareous shell to prevent drying. They contain a yolk to nourish the embryo, which emerges from the egg as a small facsimile of the adult. In Amphibia and fish the eggs have no protective covering, and must be laid in water. They are small, without yolk, and therefore the embryo hatches out before its development is complete ; in the case of the Amphibia, as we have already noted, it swims about in water, while its legs and lungs and other features necessary for life on land are developing. In a few living lizards and snakes the females bring forth their young alive, and some extinct reptiles were certainly viviparous.

Reptiles include many forms, such as lizards, snakes, alligators, crocodiles, tortoises and turtles, which are still living ; and others—dinosaurs, flying reptiles, and marine ichthyosaurs and plesiosaurs—which did not survive the Mesozoic, the era of reptilian dominance. Reptiles are cold-blooded, and have a body covering of scales or bony armour. There is one occipital condyle. In modern reptiles the teeth are usually pointed and recurved ; in some extinct reptiles they were also adapted for the cutting and mastication of food. Another peculiarity in some fossil forms was a well-developed pineal eye.

Reptiles have shown extraordinary adaptability of organization to varied environment, and in this respect are comparable to mammals. They have proved themselves capable of many different means of progress on land—crawling (snakes), swift running (bipedal dinosaurs), sprawling over muddy surfaces (certain primitive forms and certain modern lizards); for life both on land and in water (crocodiles and turtles), for life wholly in water, and for flight through the air.

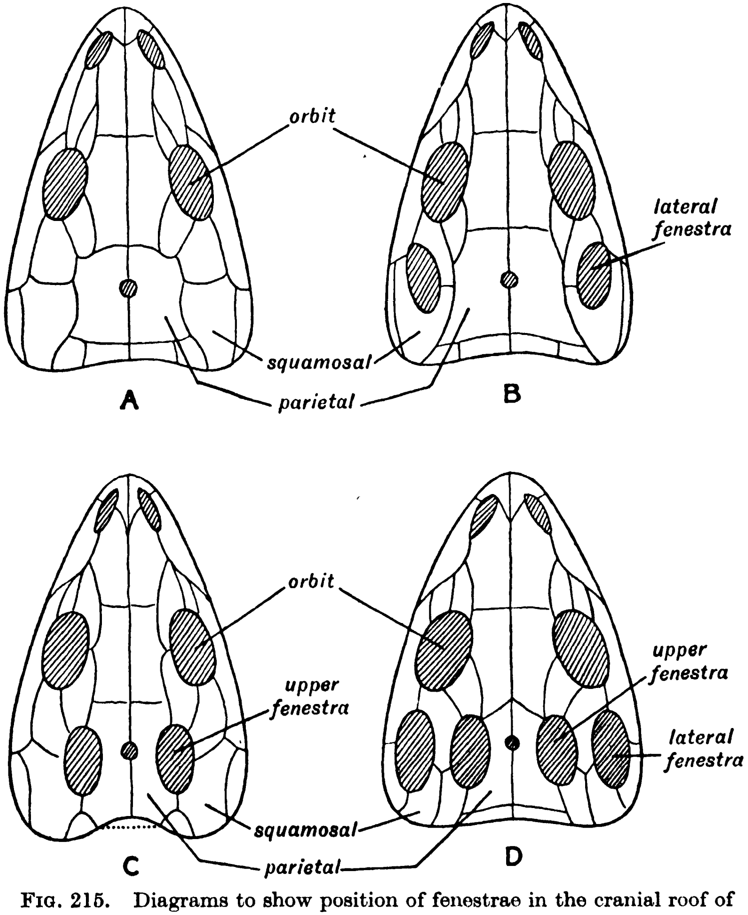

FIG. 215. Diagrams to show position of fenestrae in the cranial roof of reptiles. (After Broom.)

A. Anapsida. B. Synapsida. C. Parapsida. D. Diapsida.

The first reptiles probably appeared before Upper Carboniferous times, but the earliest known with any completeness come from the Lower Permian of Texas and later from the Permian and Trias of South Africa, Russia and Britain. These early reptiles are so imperfectly known that classification is difficult, but the main groups can be recognised by the arrangement of the bones in the temporal region of the skull. There, certain bones or combinations of bones tend to contract in broad arches, leaving openings or vacuities (fenestrae) behind the eye-sockets. Four arrangements of the fenestrae are recognised (Fig. 215) :

1. Without fenestrae : roof of skull continuous (Anapsida).
2. With lateral fenestrae (Synapsida).
3. With upper fenestrae (Parapsida).
4. With lateral and upper fenestrae (Diapsida).

The sub-class ANAPSIDA were represented among the early reptiles by the primitive order Cotylosauria of the Permian and Trias, which closely resembled their anapsidian stegocephalian ancestors in the structure of the skeleton. The distinction of the two groups requires a more detailed knowledge of the vertebrate skeleton than can be given here, but in the Cotylosauria there was a tendency to reduce the body armour and the relative size of the skull. They were sluggish creatures (Fig. 216), sprawling or waddling on land, though in some cases they probably could swim quite well by means of their long tails. *Elginia* (Fig. 217), from the Permian of Elgin, belonged to this order. Only the skull is known ; it had a pineal foramen for the third eye (see Fig. 217 and p. 335) ; the bones were coarsely sculptured ; there

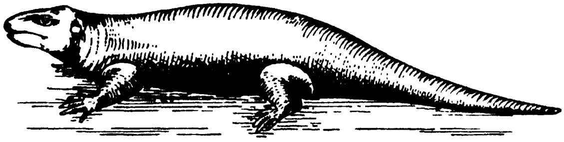

FIG. 216. *Diasparactus*, a cotylosaur. (After Williston.)

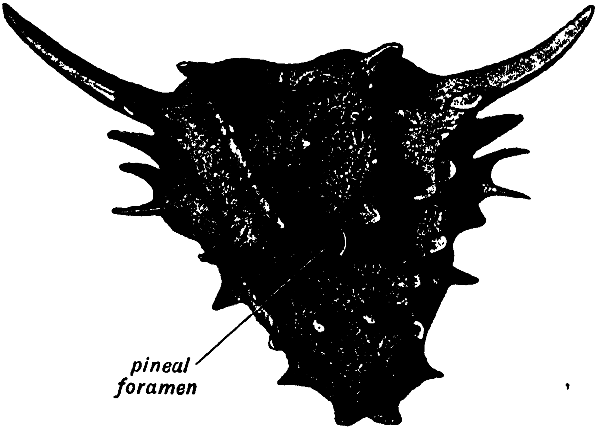

FIG. 217. Skull of *Elginia*, a cotylosaur. (After Newton.)

were paired tubercles on the facial region, and spinous processes at the sides, the upper ones on each side being enlarged like horns.

The early Chelonia (the order of the tortoises and turtles) have continuous cranial roof, and are now generally regarded as derived from the Cotylosauria. The body is covered by a carapace formed of elements from both the endoskeleton and exoskeleton. The chelonians are first known from the Upper Keuper of Southern Germany and have yielded numerous fossils. They have undergone no noteworthy modifications of structure during their long geological history.

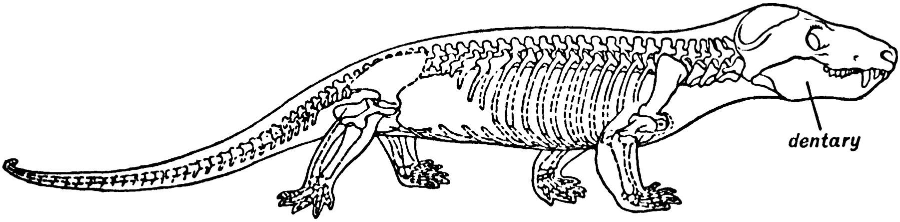

FIG. 218. *Cynogathus*, a cynodont reptile of the Trias. Note the differentiated teeth and large dentary. (After Gregory and Camp.)

The SYNAPSIDA are represented by the order Theromorpha, so called because of the many resemblances in the skeleton to that of the mammals. In the latest members (the division Cynodontia of the sub-order Theriodontia), as in the mammals, the teeth were differentiated and localized into incisors, canines, pre-molars and molars, and the lower jaw consisted almost entirely of the two dentary bones as in mammals, the other bones of the reptilian lower jaw being reduced to a little cluster behind, at the articulation with the skull (Fig. 218). The Cynodontia are therefore of special importance in furnishing a reptilian link between the mammals and the early amphibia, for they were closely connected through the Cotylosauria with the Stegocephalia. Not all the theromorphs had mammalian dentition ; they are a varied group, and a few examples of special or local interest may be mentioned. Among carnivorous forms the curious *Dimetrodon* (Fig. 219), from

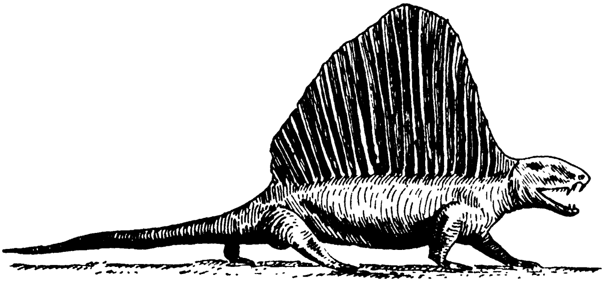

FIG. 219. *Dimetrodon*. (After Romer.)

the Permian of Texas had greatly elongated neural spines that formed a high crest over the back. In the sub-order Dicynodontia the teeth were more or less suppressed, and the jaws were probably clothed in horn, forming a beak over the solid projecting symphysis of the upper jaw.

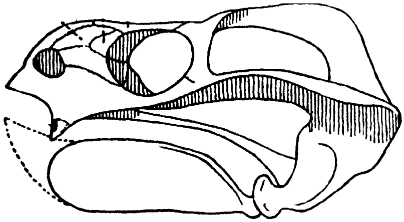

FIG. 220. Skull of *Gordonia*. (After Newton and Woodward.)

The dicynodonts are represented in the Permian of Elgin by the genera *Geikia* and *Gordonia* (Fig. 220). The former was toothless, the latter had small tusks in the upper jaw.

Ichthyosauria (Fig. 221) are perhaps the most important and most striking order of PARAPSIDIAN REPTILES. With their fish-like, stream-lined body, hypocercal tail-fin and limb-paddles, they were perfectly adapted to a life passed entirely in water. The snout was long and tapering, and the conical teeth were inserted in a continuous groove. Each large eye-socket was furnished with a ring of bony, sclerotic plates. The paddle-like form of the limbs was achieved by shortening the proximal bones and the multiplication of the small bones of the fingers and

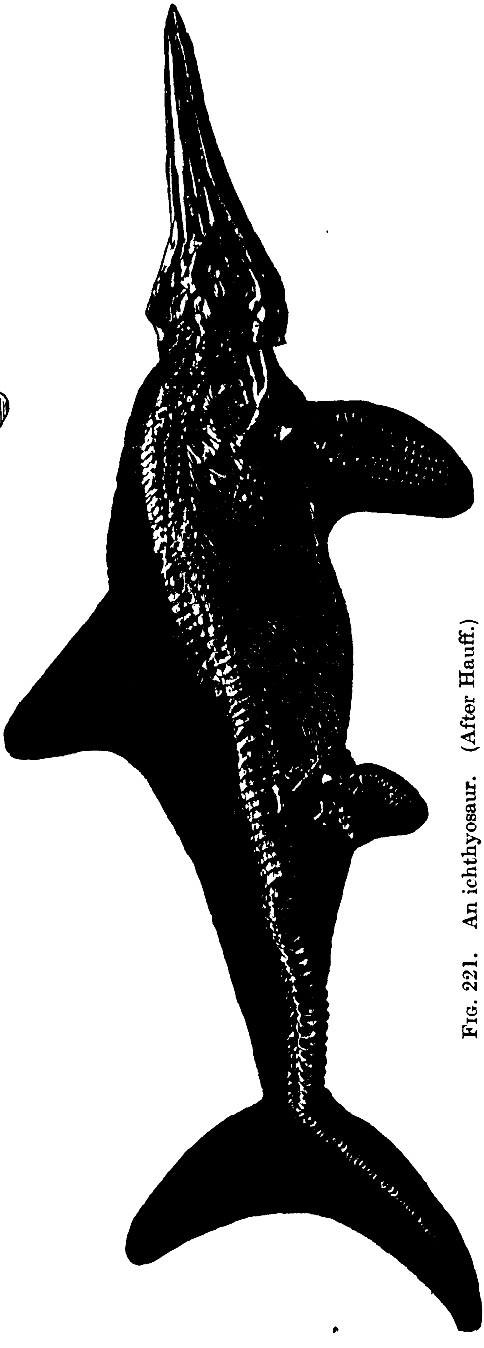

FIG. 221. An ichthyosaur. (After Hauff.)

toes (*cf.* Fig. 221). As their adaptation to aquatic life was complete, the ichthyosaurs could not return to land to lay eggs and were viviparous. They occurred throughout the Mesozoic, and by Cretaceous times had achieved almost world-wide distribution.

In another order, the Sauropterygia, the limbs were transformed into paddles by similar modifications of the limb-skeleton (Fig. 222), but in other respects the adaptation to aquatic life was not so complete as in the ichthyosaurs. The head and body were not fish-like and these animals retained a limited power of movement on land, to which they doubtless went for egg laying. They originated in the Trias of Eurasia, and were widely distributed at the time of their extinction in the Upper Cretaceous.

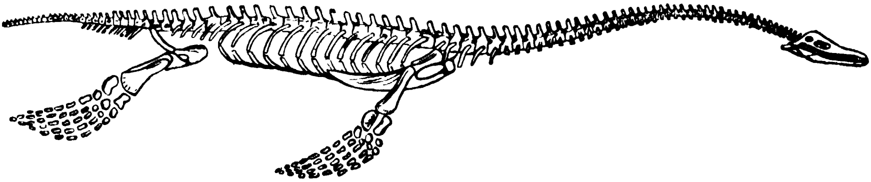

FIG. 222. *Plesiosaurus*, a sauropterygian. (After Conybeare.)

No creatures, living or extinct, have a more powerful appeal to the imagination than the Dinosaurs, a remarkable DIAPSIDIAN GROUP that dominated the lands of the Mesozoic and produced some of the largest and most bizarre animals that ever lived. It is impossible in the space at our disposal even to mention all the types produced by the creative exuberance of this fertile stock, let alone to describe the conditions of their existence or to discuss the biological puzzle of their sudden extinction at the end of the Mesozoic after dominating the lands for millions of years. We can only indicate the main systematic divisions of the order with some of their representative genera and refer those who wish to pursue the subject in greater detail to an interesting and comprehensive account, ' The Dinosaurs ', by W. E. Swinton (Murby).

The earliest diapsidian reptiles were small crawling animals from the Upper Permian of South Africa. They had short snouts, large orbits (eye-sockets) and large pineal foramen. They are referred to the sub-order Eosuchia. A closely related and possibly derivative group, the Pseudosuchia, were more widely distributed in Triassic rocks (South Africa, America, Germany and Scotland). They were small, slender, agile reptiles, with long hind legs, and differed from the Eosuchia in the absence of the pineal foramen and in other skeletal details. The Pseudosuchia are of special importance because they probably gave rise, not only to the dinosaurs, but also to the crocodiles, the pterosaurs and the birds. The little *Scleromochlus* (Fig. 223) from the Upper Trias of Elgin, an undoubted dinosaur, was so similar to some of the

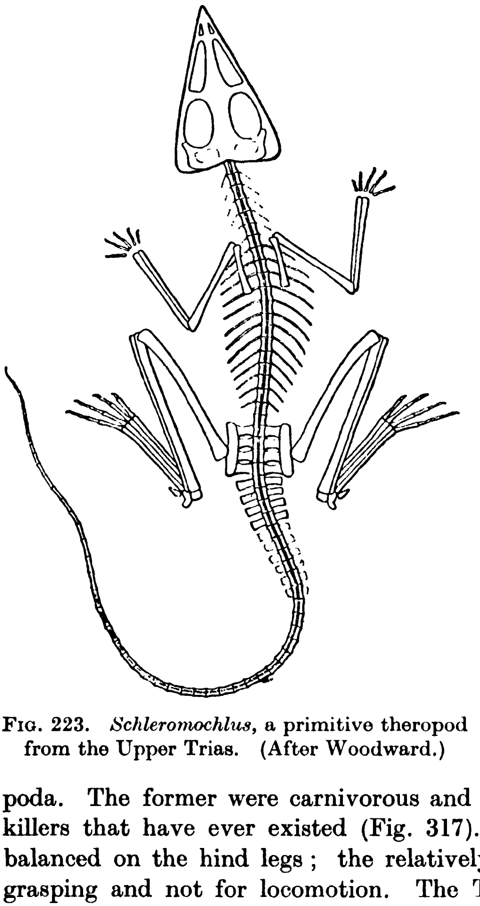

FIG. 223. *Schleromochlus*, a primitive theropod from the Upper Trias. (After Woodward.)

Pseudosuchia that it has been included by some authorities in that sub-order.

The Dinosaurs did not constitute a homogeneous order, but comprised two groups that were derived at different times from the pseudosuchian radical, and were distinguished by the structure of the pelvis. The Saurischia had the normal reptilian pelvis. The Ornithischia had the pelvis much like that of a bird, although there is probably not complete homology of the parts. The usual interpretation of the ornithischian pelvis is indicated in Fig. 224, but it is now thought that the structure labelled 'post-pubis' is the retroverted pubis, while the 'pubis' is a prae-pubis of secondary origin developed for abdominal support.

The Saurischia comprised two sub-orders, the bipedal Theropoda and the quadrupedal Sauropoda. The former were carnivorous and comprised the largest terrestrial killers that have ever existed (Fig. 317). The body and long tail were balanced on the hind legs; the relatively short fore-limbs were used for grasping and not for locomotion. The Theropoda ranged from Trias to Upper Cretaceous. The Sauropoda were herbivorous and include among

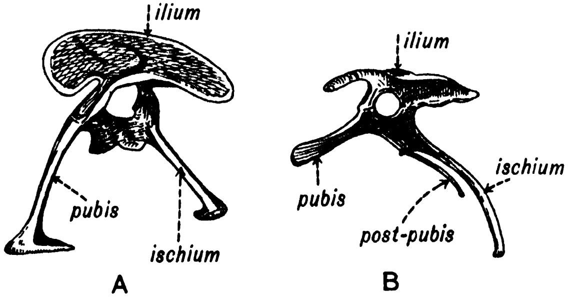

FIG. 224. Two types of dinosaurian pelvic girdle.
A. Saurischian. (After Marsh.) B. Ornithischian. (After Zittel.)

their number the largest animals that ever walked. The relatively short body was supported on four pillar-like legs; neck and tail were long, especially in *Diplodocus*, one species of which measured 85 feet (Fig. 225). From what is known of their contemporary geographical milieu in coastal swamps, it seems likely that these giant forms were amphibious, resorting to land only on occasion. Details of the skeleton suggest that much of their time was spent with the body almost entirely submerged, the water affording partial support to the colossal bulk and weight. The sauropods ranged from Jurassic to Upper Cretaceous.

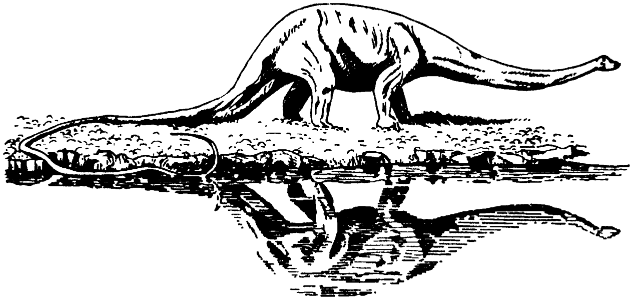

FIG. 225. *Diplodocus*. (Modified after Swinton.)

The Ornithischia, like the Saurischia, may be conveniently divided into bipedal and quadrupedal forms, both being herbivorous. The bipedal Ornithischia are called Ornithopoda, because their three-toed feet resembled those of cursorial birds like the ostrich. There were other bird-like features in the skeleton (including a horny beak) and it is probable that the Ornithopoda and birds were closely related to a common pseudosuchian ancestral stock. The fore-limbs were shorter than the hind-limbs and had prehensile hands; this circumstance and the structure of their teeth suggest that they browsed on the foliage of trees. The best-known genus is *Iguanodon* (Fig. 226). The first records of the genus came from the Wealden Beds of Sussex, but much of our

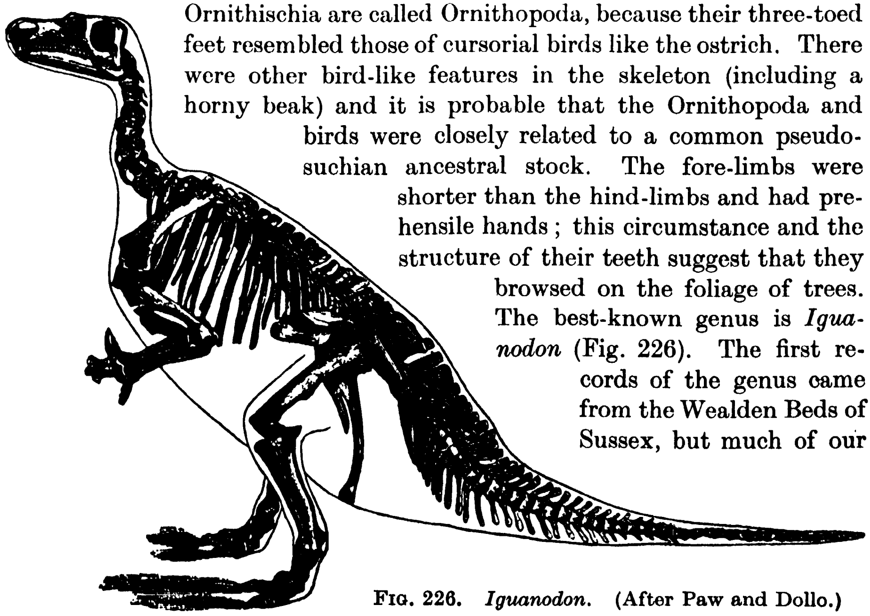

FIG. 226. *Iguanodon*. (After Paw and Dollo.)

knowledge of the skeleton is due to a startling discovery during mining operations of twenty-nine skeletons in a rock-fissure at Bernissart in Belgium. Most of these have been mounted in the Natural History Museum in Brussels, where they form a remarkable group. *Iguanodon* was one of the large ornithopods, attaining a length of 30 feet, inclusive of the long flattened tail, and standing about 15 feet high. A curious feature of the hand in *Iguanodon* is a spike-like thumb. The Ornithopoda ranged through the Mesozoic and were widely distributed.

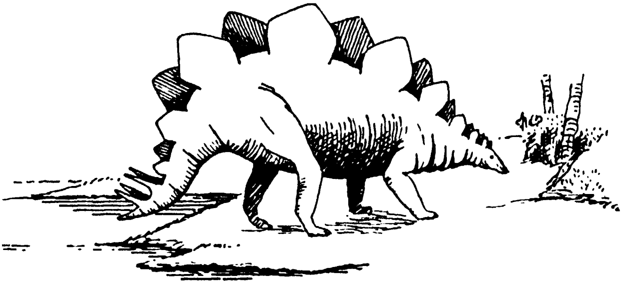

FIG. 227. *Stegosaurus.* (After Swinton.)

The quadrupedal Ornithischia were the armoured dinosaurs. They were descended from the bipedal Ornithopoda, which they resembled in features of the skeleton and in the horny beak. There were two groups, to which some authorities give sub-ordinal rank—(1) the Stegosauria with a defensive armour of bony plates, and (2) the Ceratopsia, or horned dinosaurs. The first group comprised (*a*) Jurassic forms like *Stegosaurus* (Fig. 227), in which the armour took the form of two rows of erect, flattened plates along the back to protect the spine, and two pairs of spines on the stumpy tail, and (*b*) Cretaceous forms, in which the body was uniformly plated all over. These last had low, barrel-like bodies and cumbrous movements (Fig. 228). *Stegosaurus* attained a length of over 25 feet, and had a higher and narrower body than the fully armoured forms, with the head carried near the ground in a suitable

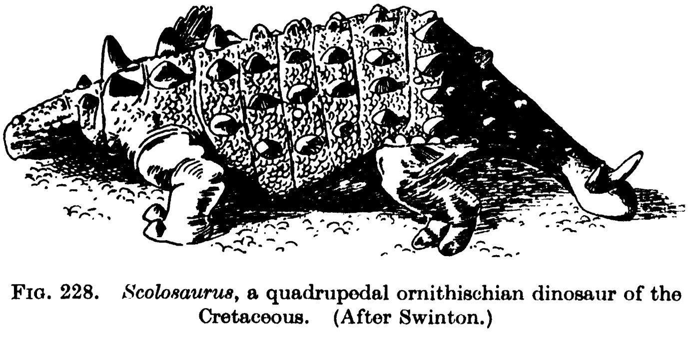

FIG. 228. *Scolosaurus*, a quadrupedal ornithischian dinosaur of the Cretaceous. (After Swinton.)

position for browsing the succulent vegetation as they lumbered along beside the marsh-lands, where wallowed the gigantic sauropods.

In the Ceratopsia the only protective armour was a gigantic bony frill protecting the vulnerable parts of the neck. The offensive armature was provided by bony horns on the face. In *Triceratops* (Fig. 229), the best known of the Ceratopsia, there were three of these horns, two long ones over the orbits and a shorter one on the nose. The creature is curiously reminiscent of a giant rhinoceros. With its battery of horns carried near the ground impelled by a ten-ton body, *Triceratops* must have been a formidable adversary in attack. The Ceratopsia were the last of the dinosaurs to appear. They are confined to the Cretaceous and are characteristically Upper Cretaceous.

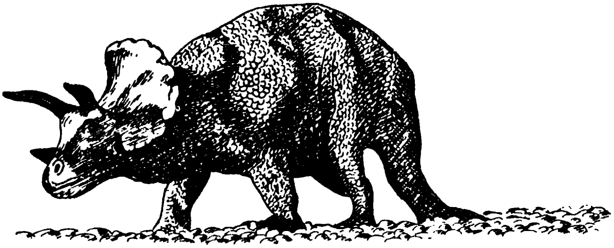
FIG. 229. *Triceratops*. (After Swinton.)

Closely related to the early diapsidian stock that gave rise to the dinosaurs were the Rhynchocephalia, short-necked reptiles whose long tail and feeble limbs indicate that they spent much of their time in water. The front teeth were enlarged and beak-like. Appearing in the Permian they achieved an acme in the Trias. They have a special interest because their sole modern representative, the lizard-like tuatara of New Zealand (*Sphenodon*), retains the pineal eye on the top of its head. Both lens and retina are present, but the eye is covered with skin and no longer functions. There is an opening in the skull of *Sphenodon* to accommodate this third eye; a similar pineal foramen occurs, as we have seen, in some extinct reptiles in which the eye was probably functional.

The Squamata (lizards and snakes) are closely related to the Rhynchocephalia and probably the two groups had a common

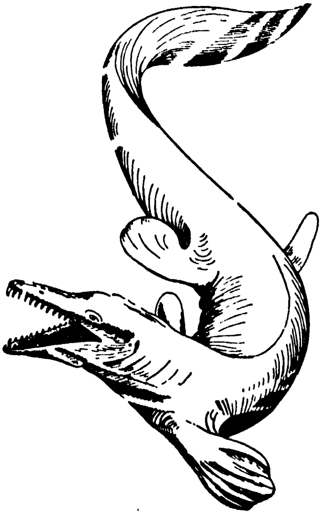
FIG. 230. *Clidastes*, a mosasaur. (After Williston.)

ancestor. Fossils of lizards are few. The first that can be definitely assigned to the sub-order come from Cretaceous rocks. Fossils of snakes are even rarer, the earliest occurring in the Neocomian (Lower Cretaceous). The Squamata gave rise to a remarkable group of extinct marine reptiles, which had a restricted vertical range and wide geographical distribution. These were the Pythonomorpha, often called mosasaurs, from the name of their best-known family, the Mosasauridae. The lizard-like body (Fig. 230) attained a length of 40 feet and was as perfectly adapted to marine life as in the earlier ichthyosaurs. There was a similar paddle-like modification of the limbs, an interesting example of convergence of structure in different stocks in adaptation to a common mode of life.

FIG. 231. *Rhamphorhynchus*, a pterosaur. (After Stromer.)

The Pseudosuchia gave rise also to the crocodiles, amphibious or aquatic diapsidian reptiles, that range from Lias to present day and are represented by numerous fossils. Of more obscure origin were the diapsidian Pterosauria, extraordinary flying reptiles of the Jurassic and Cretaceous, in which the fifth digit of the hand was enormously elongated and flexed to support a wing-membrane (Fig. 231). It is certain that they were more clumsy in flight than the birds. These latter were probably also derived from the Diapsida, but when and where they diverged from the reptiles and assumed feathers is unknown.

CHAPTER LIII

CHORDATA: CLASS AVES

THE birds are warm-blooded vertebrates with feathers. The fore-limbs are modified to wings for flight. The earliest known birds, from the famous lithographic stone of Solenhofen (Upper Jurassic), had already acquired these features. They are represented by two skeletons of different species that are either referred to a single genus, *Archaeopteryx*, or to two genera, *Archaeopteryx* and *Archaeornis*, the latter being represented by the more complete skeleton, now preserved in the Berlin Museum (Fig. 314).

The feathers were ranged along the hinder borders of the fore-limbs and along either side of the fully developed tail, and three clawed digits of the hand were visible. The jaws contained conical teeth. In modern birds three digits are still present in the hand, but claws and some finger-bones have disappeared, while a firm foundation for the wing has been provided by fusion of the distal bones of the limb (*cf.* the wing supports in pterosaurs and bats). Some birds, like the ostriches and the recently extinct moas of New Zealand, have lost the power of flight. The moas furnished the largest known bird, *Dinornis*, which attained a height of 10 feet. Fossils of birds are rare, possibly because of their alertness in avoiding dangers of the kind that would lead to burial on land, and our knowledge of their evolution since the days of *Archaeopteryx* is imperfect. The gap between *Archaeopteryx* and the Cretaceous birds is very wide, although the latter still had teeth. Nor is there any bridging of the gap between the birds of the Cretaceous and those of the Eocene. They must have made continuous progress during the Kainozoic for they are highly diversified and successful at the present day.

CHAPTER LIV

CHORDATA : CLASS MAMMALIA

THE majority of the Mesozoic reptiles evolved in directions that led to the modern reptiles, to the birds, or to extinction. To resume consideration of the main trend of vertebrate evolution that culminated in man, we have to return to the Theriodontia and especially to one section of this reptilian sub-order, the Cynodontia (Fig. 218), which were widely distributed in the Trias (South Africa, Russia and Brazil). In general appearance the cynodont skull was like that of a small carnivorous mammal, with the teeth arranged as incisors, canines, pre-molars and molars (*cf.* p. 339). In addition the bones of the brain-case and lower jaw had certain typically mammalian features while retaining reptilian characters in a modified condition. There can be no doubt that among the cynodonts occur the passage-forms that link the mammals to the reptiles.

The mammals formed only an inconspicuous fraction of the land fauna of the Mesozoic. It is difficult to account for this long term of obscurity, for the Mesozoic mammals can hardly have come into direct competition with the dominant dinosaurs. Certainly during this period of seclusion improvements of brain and changes in the methods of nourishing the young were effected. These, coming to fruition together near the end of the Mesozoic when a tempering of climate over large areas produced congenial conditions for active warm-blooded creatures, may have afforded the stimulus that brought the mammals rapidly to dominance over the Kainozoic lands.

The mammals are warm-blooded vertebrates with mammary glands that secrete milk when the female is nursing the young. Externally they are more or less covered with hair. In mammals the brain attains its highest development, becoming most strongly convoluted in man himself. The body cavity is divided by a muscular partition, the diaphragm, into a thoracic cavity containing the heart and lungs and an abdominal cavity containing the rest of the viscera. In most mammals there are two sets of teeth—the milk teeth which eventually fall out, and the permanent teeth. In fish and reptiles teeth are numerous and new teeth can replace old teeth indefinitely. In primitive mammals the maximum number is 44 ; there are 32 in man. Instead of being simply conical they are varied according to function and grouped as incisors, canines, pre-molars, and molars. The milk teeth are fewer and smaller than the permanent teeth ; thus there are no milk teeth corresponding with the molars, the pre-molars of the permanent dentition replacing the cheek teeth of the milk set. The dental formula indicates briefly the number of teeth of the various kinds in the upper and lower half jaw, and is of great diagnostic value. Thus the dental formula in man is :

$$\frac{\text{upper half jaw } 2i - 1c - 2pm - 3m}{\text{lower half jaw } 2i - 1c - 2pm - 3m} \quad \text{or} \quad \text{more briefly } \frac{2\,.\,1\,.\,2\,.\,3}{2\,.\,1\,.\,2\,.\,3}.$$

The visible part of the tooth is the crown, below is the root, sunk in the jawbone. In the cheek teeth (pre-molars and molars) the crown bears small tubercles or cusps on the grinding surfaces for masticating food before swallowing. A fleshy cheek prevents the food falling out of the mouth during mastication.

The teeth have high systematic value, but are to be used with due caution, for it must be remembered that they are adapted to the animal's food and that unrelated stocks with similar dietary may develop similar dentition. Owing to the hardness of their enamel, teeth are the most frequently preserved mammalian fossils. The arrangement and form of the molar cusps are exceedingly diverse and of the greatest systematic importance. A primitive tritubercular type, in which three conical cusps are arranged in a triangular pattern, with two cusps on the cheek side and one on the tongue side in the upper jaw, and the converse arrangement in the lower jaw, is the common starting point for the evolution of all types of mammalian molars during the Kainozoic.

There are three main types of mammalian organization, reflecting the arrangements for nourishing the young in the earliest period of growth and possibly representing stages in the evolution of the class. They form a basis for the definition of three subclasses. In the first subclass, PROTOTHERIA, which comprises only one order, the Monotremata, the female lays eggs. The few living representatives, of which the duck-mole or duck-billed platypus (*Ornithorhynchus*) is perhaps the most familiar, are confined to the Australian region and give little idea of the Prototheria in their heyday. Unfortunately the characteristic features belong to the soft parts and the recognition of fossil Prototheria by means of skeleton alone is a difficult matter. The few remains that can be definitely ascribed to the Prototheria belong to the three recent genera and are found in the Pleistocene of Australia, their modern habitat.

The second type of mammalian organization is represented by the marsupials (opossums, kangaroos, etc.), or METATHERIA. The young are born in an immature state and are carried attached to the breasts of the mother in an abdominal pouch, the marsupium.

In the last of the three main stages of mammalian evolution, the EUTHERIAN, the young are nourished by the placenta, a special growth, partly of foetal and partly of maternal origin, by means of which the embryo is attached to the mother and nourished during gestation, enabling the young to be born in a relatively mature state. Most of the Kainozoic including Recent Mammals are Eutheria, and they dominated the lands of Kainozoic times.

Only a relatively small number of Jurassic mammalian fossils are known. They are all fragmentary, consisting mostly of detached teeth, mandibles, limb-bones and an occasional skull. They are grouped in the heterogeneous subclass ALLOTHERIA, a procedure that is convenient and does not imply close affinity with any one of the three great subclasses of Kainozoic and recent mammals. Four distinct allotherian orders are recognised. There are no definite clues to their inter-relationships. Their common ancestry is probably to be looked for among the cynodont reptiles. The oldest of these orders, the Multituberculata, ranged from Rhaetic to Lower Eocene and hence had a longer existence than any other group of mammals. They are characterized, as the name Multituberculata implies, by many-tubercled cheek-teeth, the tubercles being arranged in two or three parallel rows on the grinding surface of the tooth. Familiar examples are the tooth *Microcleptes* [*Microlestes* (*pars*)] of the Rhaetic (Fig. 232A, B) and *Plagiaulax* (Fig. 232C) a jaw from the Purbeckian. It is now thought that the Multituberculata were perfectly adapted to a herbivorous diet, a circumstance that kept them from competition with their small insectivorous and carnivorous contemporaries of the Mesozoic, and enabled them to survive until replaced by the more progressive herbivorous placentals of the early Kainozoic.

In the Triconodonta, an allotherian order of the Middle and Upper Jurassic, the molars had three cusps arranged longitudinally (Fig. 232D). In the simplest type the anterior and posterior cusps were small and obviously derivable from similarly placed excresences on a simple cone of reptilian type, as, for example, in the Upper Triassic or Rhaetic *Dromatherium* (Fig. 232E), which is now known to be a cynodont reptile. In the Symmetrodonta of the Upper Jurassic three cusps are arranged in a symmetrical triangular pattern (Fig. 232F). In the Pantotheria (Middle and Upper Jurassic) the primitively trigonal molars become more elaborate (Fig. 232G). Other features of the teeth and jaw suggest that this order may represent the stock from which both marsupial and placental mammals arose, but there is an enormous gap between Upper Jurassic (Purbeck in England; Morrison in America) and Upper Cretaceous, where the next mammalian fossils are found, and these are not pantotheres.

The mammals of the Upper Cretaceous are surviving multituberculates together with the first definitely determinable marsupials and placentals. The Upper Cretaceous marsupials are opossums from Western America, and their fragmentary fossils are sufficient to show that this family was then in existence, and thus surpasses in antiquity any family of recent mammals. In Pleistocene and Recent times the METATHERIA are confined to America and

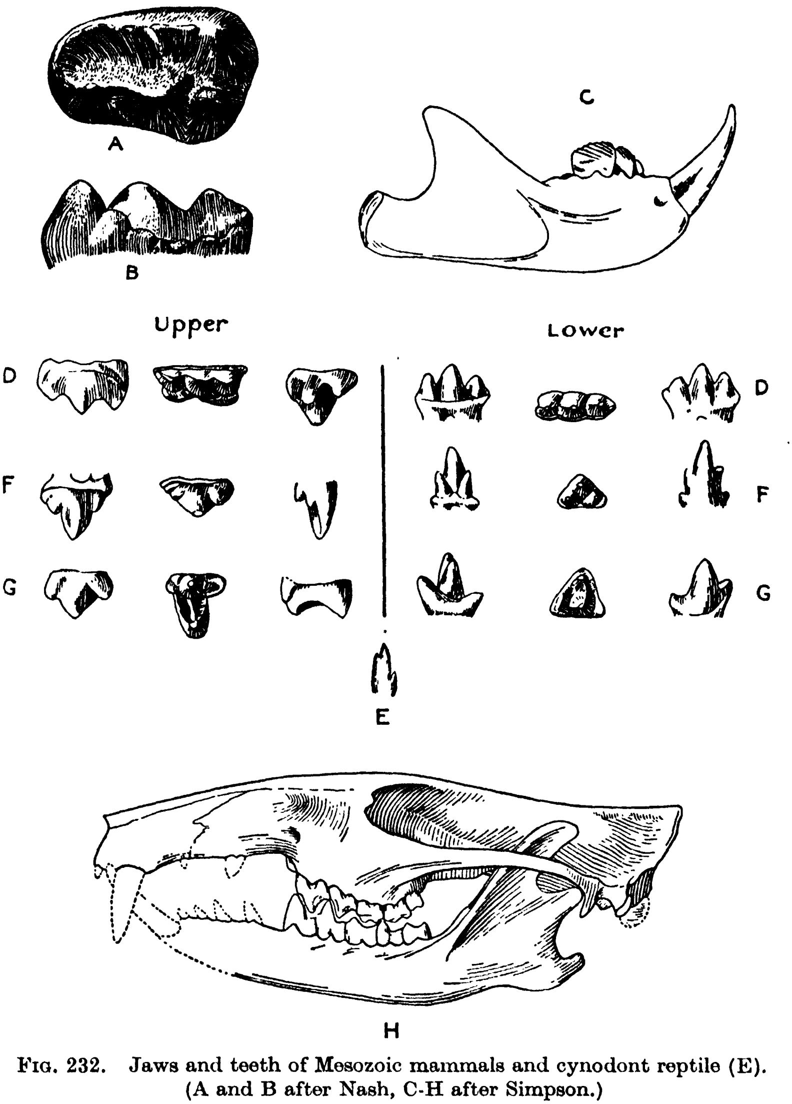

FIG. 232. Jaws and teeth of Mesozoic mammals and cynodont reptile (E). (A and B after Nash, C-H after Simpson.)

A and B. *Microcleptes*. C. *Plagiaulax*.
D. Triconodont molars. E. Molar of *Dromatherium*.
F. Symmetrodont molars. G. Pantotherian molars.
H. Skull of Mongolian Cretaceous insectivore.

Australasia, but in the earlier Kainozoic they occurred commonly in the Old World as well as in America. Nothing is known regarding the origin of their modern Australian representatives.

The placentals of the Upper Cretaceous are assigned to the order Insectivora (moles, shrew-mice, and hedgehogs) which comprises a number of diversely specialized and distantly related groups of primitive EUTHERIA, with characteristically flattened skulls. In habit they are frequently burrowing and nocturnal, which, in conjunction with their diet of insects and worms, has kept them from competition with other animals. The primitive insectivores are represented by well preserved skulls from the Upper Cretaceous of Mongolia (Fig. 232H). Those of the earliest Kainozoic show a certain degree of specialization, notably of the ankle, which renders it probable that they are ancestral to only a fraction of the other Eutheria, such as rodents and edentates.

The history of the placental mammals of the Kainozoic falls into two great periods. The earlier was, until recently, regarded as of brief duration and termed ‘ basal Eocene ’. Now, however, as the Paleocene, it is regarded as one of the major divisions of the Kainozoic, equivalent to Eocene, Oligocene and other periods. It is characterized by small placental mammals whose primitive and generalized structure adds greatly to the difficulty of systematic treatment. They had short limbs with five digits, long tails and small brains (Figs. 235, 236) and included representatives, not only of the insectivores, but of other primitive orders which appear suddenly in the Paleocene of New Mexico, without any record of their pre-history. A few of these orders bridge the later palaeontological hiatus that separates the Paleocene from Lower Eocene, but some became extinct in face of the competition of the modernized mammals. These ancient mammals of the Paleocene and especially the Insectivora, Creodonta, and Condylarthra (see below, p. 344) give us a picture of the types of centralized creatures from which radiated the various orders of modernized placental mammals, for the most part already defined by Lower Eocene times.

The sudden irruptions of the Paleocene mammalian fauna and then of the Lower Eocene fauna into the palaeontological record are very interesting problems, but difficult to solve with the imperfect records at our disposal. It is only possible to mention various factors that may have contributed to this repeated phenomenon. Lapse of time (disconformity) and change of facies may each have played a part. More important perhaps was migration from unknown centres of dispersal, first in the Cretaceous then in the Paleocene, in response to phases of the great mountain making movements of late Cretaceous and early Kainozoic.

We have now to survey briefly the various orders of Kainozoic (including Paleocene) mammals.

The bats (Chiroptera) are a group of specialized primitive insectivores. They occur rather sporadically as fossils, but are of special interest as the only group of mammals to become adapted for flight. It is interesting to compare their equipment with that of birds and of pterosaurs. The fore-arm is much longer than the upper arm, and four digits of the hand are enormously elongated, though the thumb remains short and opposable (Fig. 233).

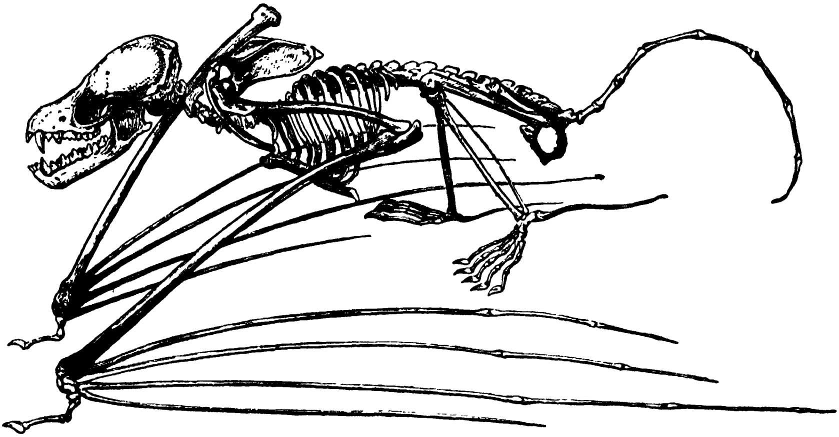

Fig. 233. Skeleton of a bat, *Vespertilio*, Miocene to Recent. (After Blainville.)

The elongated digits are united by skin, which is stretched to join not only with the hinder part of the body, but also with the tail and an elongated spur of the heel.

Rats, rabbits, squirrels, etc., with their extinct ancestors, form the homogeneous order Rodentia, which was possibly derived from primitive insectivores. They are characterized by very long, sharp incisors, for gnawing. They are herbivorous, and mostly burrowers, but some are adapted for arboreal life and others for swimming. Their first determinable fossils occur in the Lower Eocene of North America, and they have furnished numerous remains in subsequent formations.

The origin and relationships of the order Edentata are still a mystery. These strange creatures —armadillos, sloths, ant-eaters— are utterly unlike other mammals and are yet diverse in themselves. Only the ant-eaters of South America and the Old World are properly described as toothless. The order ranges from Eocene and yields many interesting fossils, including the recently extinct giant sloth, *Megatherium* (Fig. 234), of America.

Fig. 234. *Megatherium*. (After Scott.)

The order Carnivora comprises a great variety of extinct forms as well as the modern terrestrial forms (cat, dog, bear, etc.) and the aquatic seals and walruses. The primitive carnivora of the sub-order Creodonta (Fig. 235) appeared in the fauna of the Paleocene. They were related to the true carnivores, from which they are distinguished by their smaller and feebly convoluted brains and in details of dentition. It is difficult to give any definite structural diagnosis of the group. The teeth were primitive, or specialized into various predaceous or omnivorous adaptations, brain-case small, feet mostly pentadactyl and clawed, plantigrade or digitigrade and weak in construction. In size they range from creatures no larger than a rat to the giant *Andrewsarchus* from the Eocene of the Gobi Desert, the largest known predaceous mammal, with a skull over a metre in length. They achieved considerable variety of archaic specializations during the Eocene, but declined to extinction during the Oligocene in competition with their more efficient descendants, the true terrestrial carnivores of the order Fissipedia. The first Fissipedia appeared in the Upper Eocene and rapidly achieved a diversity of forms. They reached their acme in Pliocene times, but their modern representatives (dogs, cats, hyaenas, otters, etc.) are hardly diminished in numbers.

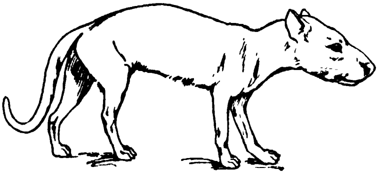

FIG. 235. *Dromocyon*, a creodont. (After Scott.)

One group of carnivores, the Pinnipedia (seals and walruses), have acquired amphibious habits. The body is somewhat streamlined, and the limbs have become paddle-like through shortening of the upper bones and the growth of webbing between the digits. Fossils are rare and occur first in the Miocene.

The carnivores produced in the Cetacea (whales, dolphins, porpoises), a stock as fully adapted to a whole-time life in water as the ichthyosaurs among reptiles. The fore limbs have become flippers and the hind limbs are either entirely degenerate or vestigial. The locomotive organ is the great, horizontally expanded tail-fin. They appeared in the Upper Eocene of Egypt with the family Zeuglodontidae, toothed forms with the formula $\frac{3 . 1 . 4 . 3}{3 . 1 . 4 . 3}$, which is common in many of the terrestrial carnivores.

The primitive order Condylarthra is regarded as a connecting link between the hoofed and clawed mammals and ancestral to most, if not all, ungulates. It is only possible to draw negative distinctions with the nearly related creodonts on the one hand and amblypods (see below) on the other. They lacked the predacious adaptations of the former and the heavy limbs of the latter. They had smaller brains than their descendants, simple joint surfaces on the limbs and all the digits were present and typically bore hoofs

(Fig. 236). Their gait was plantigrade or semi-plantigrade. They were therefore not very swift in movement, and judging from the dentition, probably omnivorous. They agreed with the creodonts in many features of their skeleton, and doubtless had a common origin. They had an even shorter existence than the creodonts, for their fossils are found only in the oldest Kainozoic deposits of Europe and North America.

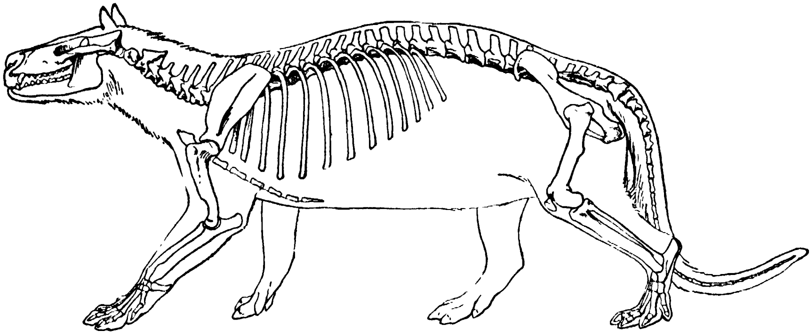

FIG. 236. *Phenacodus*, a condylarth. (After Scott.)

Before passing to consideration of the modern ungulates it is convenient to notice a group of primitive ungulates with short, heavy feet, the Amblypoda that were nearly related to the Condylarthra and appeared in the Paleocene of Western America. They produced the largest terrestrial animals of the Eocene (Fig. 237), massive creatures of about the size of a large rhinoceros, with elephantine limbs and small brains, even for primitive ungulates. Those of the Paleocene differ from the later forms in details of feet and dentition and are given subordinal or ordinal rank under the name Taligrada.

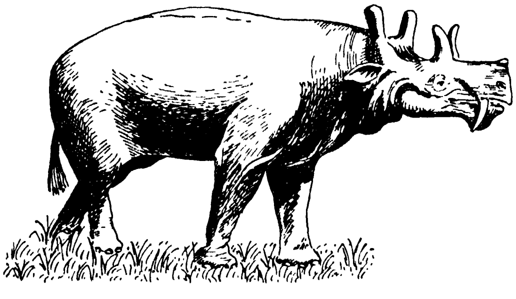

FIG. 237. *Eobasileus*, an amblypod. (After Knight.)

The modern ungulates are divided into two great orders, the Perissodactyla, with usually an odd number of digits on the foot, and the Artiodactyla, with an even number. In the Perissodactyla, which are represented at the present time only by tapir, rhinoceros, and horse, but furnish numerous fossils in Kainozoic rocks, the main axis of each foot passes through the third digit, which is usually enlarged. Both Tapiridae and Rhinoceratidae have long geological histories, the former ranging back to Lower Eocene and the latter to Middle Eocene. The distinctive horns of the rhinoceros are agglutinated tufts of hair, borne on protuberances on the nasal and sometimes on the frontal bone. The evolution of the horse from *Hyracotherium* (Fig. 238), more generally known as *Eohippus*, a small primitive perissodactyl of the Lower Eocene with relatively short limbs and four functional digits in the fore feet and three on the hind, to the large cursorial animal with which we are familiar, running swiftly on the hoofed and elongated middle digits of the feet, is a story that has become classic in the literature of evolution and need not be repeated here.* The most primitive sub-family of the Equidae, to which *Hyracotherium* belonged, was doubtless derived from the Condylarthra.

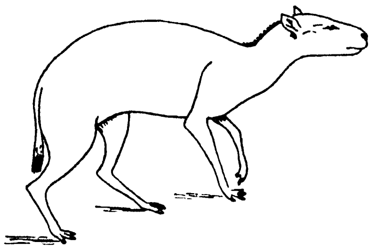

FIG. 238. *Hyracotherium.* (After Scott.)

A remarkable extinct super-family of perissodactyls, the Brontotherioidea (or titanotheres, as they are more familiarly known), flourished during Eocene and Oligocene times in North America, and produced some massive rhinoceros-like forms that were little inferior to the elephant in size. The nasal bones in the early forms carried obtuse conical protuberances which evolved into huge horns in late members of the group (Fig. 239). Like the tapirs the titanotheres combined the odd-toed and even-toed conditions, the fore limbs having four digits and the hind limbs three.

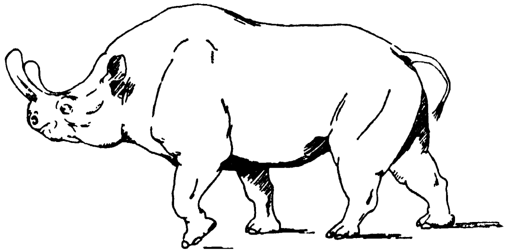

FIG. 239. *Brontotherium*, a titanothere. (After Osborn.)

The even-toed ungulates (Artiodactyla) are the dominant Ungulata at the present day, in contrast to the decadent perissodactyls. There are some fifteen families, including such familiar creatures as pigs, hippopotami, camels, deer, sheep, oxen, etc. It is impossible in a book of this kind to give an account of these even in the sketchiest of outlines, although some, like the camels, have yielded evolutionary series of great interest.

The Proboscidea (elephants) are the most familiar members of the order Subungulata. The earliest proboscidean, *Moeritherium* (Fig. 240A), from the Upper Eocene of Egypt, was a small, pig-like animal with hoofs and a nearly complete set of teeth, in which the incisors were somewhat enlarged and prominent. From this starting point the evolutionary story of the

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* For recent concise and interesting accounts of the evolution of the horse and elephant, see *Evolution* by J. Graham Kerr (Macmillan) and *A History of Land Mammals in the Western Hemisphere* by W. B. Scott (Macmillan), Revised Ed. 1937.

Proboscidea in both Old and New Worlds has been traced from an imposing mass of evidence (see footnote, p. 346) to its culmination in the elephants of India and Africa, with their great incisor tusks, weighing sometimes over 200 lbs. each, in the upper jaw only. In the course of this history, increase in size and length of limb, without compensating increase in length of neck, as in the horse, involved extension of the face in order to reach the ground. This was accomplished in the early mastodonts such as *Palaeomastodon* and its successors (which were probably not directly derived from *Moeritherium*) by lengthening the bones of the lower jaw to support a long soft proboscis-like extension of the face (Figs. 240B, 321). The shovel-like elongation of the chin showed remarkable variety of form, and in a branch stock of the Old World proboscideans, represented by *Dinotherium* * (Miocene-Pleistocene), it became recurved (Fig. 240C) together with the tusks

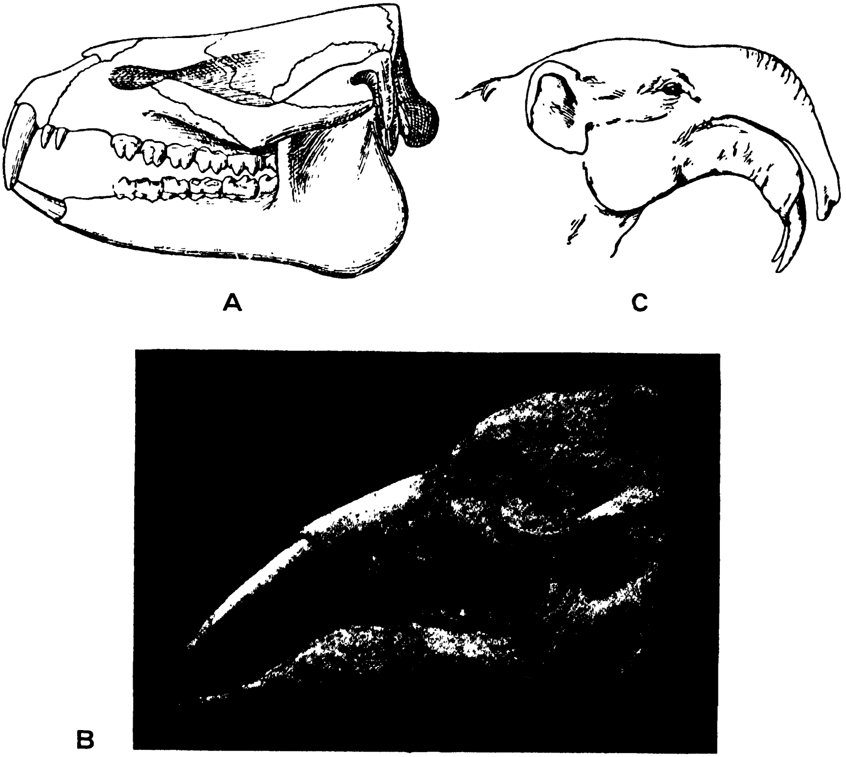

FIG. 240.
A. *Moeritherium.* (After Andrews.) B. *Trilophodon.* (After Osborn.)
C. *Dinotherium.* (After Gregory.)

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* Also *Deinotherium*. *Cf.* Deinosauria-Dinosauria, etc.

which it bore. It is now known that some of the true mastodonts had similarly recurved tusks. In later mastodonts and elephants there was a tendency to reduce the absurd elongation of the lower jaw, leaving the soft proboscis hanging free as the familiar ‘ trunk ’. The correlative change in shape of skull and in dentition are equally interesting but cannot be detailed here.

Moeritherium was a swamp-dweller, perhaps better adapted to an amphibious life than the hippopotamus, and it is therefore hardly surprising to find that the Subungulata produced an aquatic adaptation in the Sirenia (sea-cows, manatee, dugong), which frequent tropical rivers on both sides of the Atlantic and are often claimed as the basis of the mermaid tradition.

Although there is little superficial resemblance between man and the small lemurs of Madagascar, Africa and Asia, both are members of a compact, homogeneous order, Primates, which includes also the monkeys and anthropoid apes. All are plantigrade, have nails on fingers and toes, an opposable thumb (originally an adaptation to arboreal life), and other common skeletal features. The most primitive group, the lemurs (Prosimia or Lemuroidea), range back to Eocene, with a skeleton which recalls that of insectivores and creodonts. The specialization of the brain in the ape and man involved an enlargement of the brain-case with accompanying reduction of the face and shifting of the eyes to face forward. The shortening of the face reduced the number of teeth to a minimum of 32 in man. Fossils of the earliest anthropoid ape, *Propliopithecus* (Fig. 241), come from the Oligocene of the Fayûm Oasis, Egypt, the cradle (and the grave) of the progenitors of several mammalian stocks. The ape stock ultimately divided into two branches. One retained more or less the ancestral arboreal habit, the other took to the ground and culminated in man, who, stimulated by the selective effect of the rigorous conditions at the beginning of the Great Ice Age, rapidly attained supremacy.

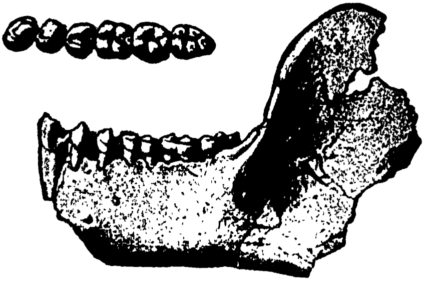


FIG. 241. *Propliopithecus*. (After Schlosser.)

Fossil remains of man (*sensu lato*) are rare. The oldest humanoid fossils, of Lower Pleistocene age, are fragmentary and differ from each other in

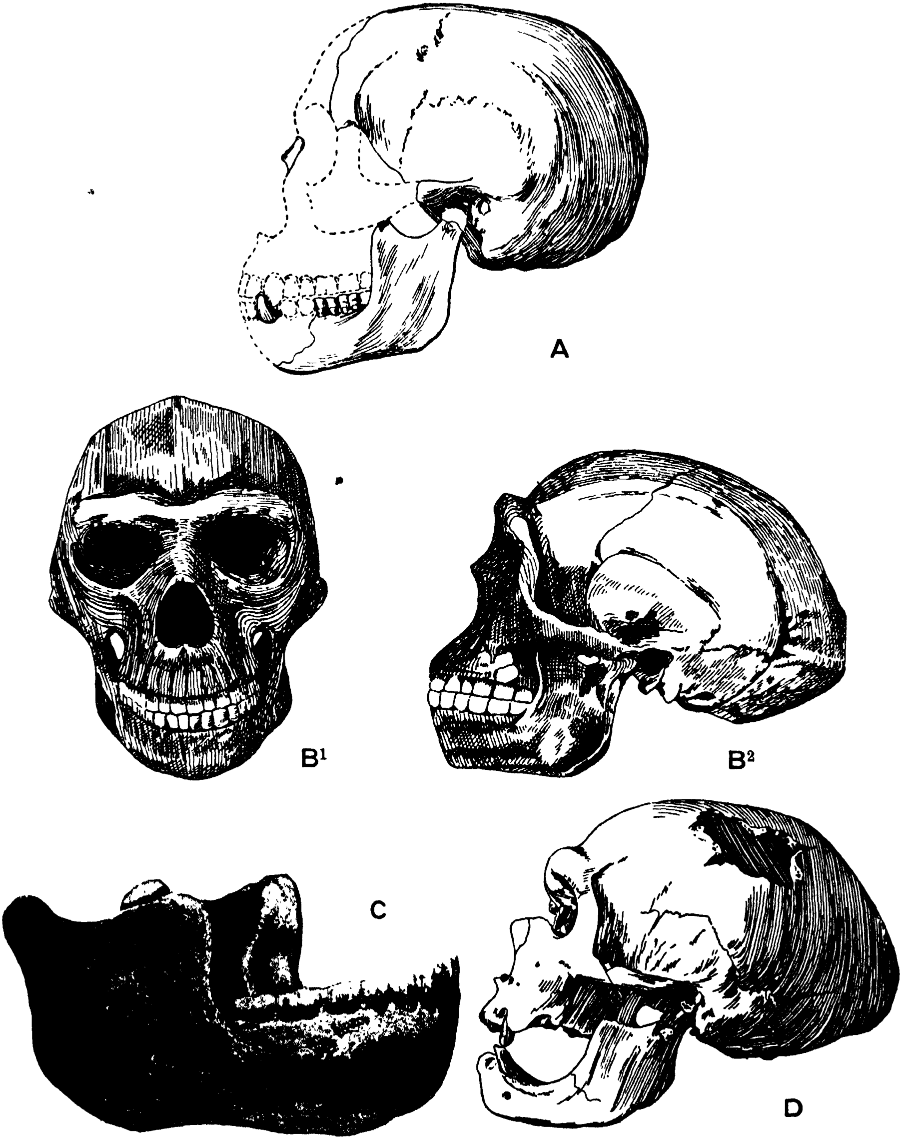


FIG. 242.

A. *Eoanthropus*, Piltdown Man. (After Smith Woodward.)

B. *Sinanthropus*, Pekin Man. Two views of a reconstructed female skull. (After Weidenreich.)

C. *Homo heidelbergensis*. The Mauer jaw, the only fossil of Heidelberg Man. (After Sollas.)

D. *Homo neanderthalensis*, Neanderthal Man. (After Boule.)

important details. Hence they are referred to different genera : *Pithecanthropus*, the ape-man of Java, represented by two skull caps, a thigh bone and some cheek teeth ; *Eoanthropus*, an imperfect skull from terrace gravels at Piltdown in Sussex (Fig. 242A) ; *Sinanthropus*, Pekin Man (Fig. 242B). All had ape-like features associated with distinctively human characters. The oldest fossil that is commonly referred to the genus *Homo* is a wide and massive lower jaw (Fig. 242C) with retreating chin that was obtained from fluviatile sand at Mauer near Heidelberg. It is called *Homo heidelbergensis*, but should perhaps be assigned to another genus, for which the name *Palaeanthropus* has been suggested. *H. neanderthalensis* (Fig. 242D), the type of Lower Palaeolithic man beloved by caricaturists, differed from *H. sapiens* in the massive eye-brow ridges, flat skull-cap, feeble chin, heavy lower jaw and large teeth. The Upper Palaeolithic Cro-Magnon man, whose drawings and paintings decorate limestone caves in the Dordogne and elsewhere (Fig. 243), is fully equal to the highest races of modern man in stature and cranial development.

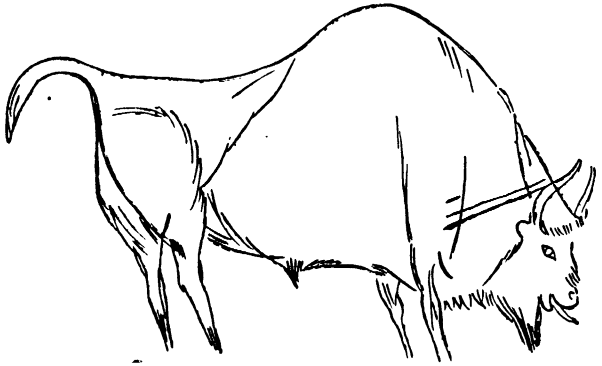


FIG. 243. Engraving of a bison from the cave of Altamira, near Santander. (After Cartailhac and Breuil.)

Human intelligence early expressed itself in the production of artifacts for various purposes. These often took the form of worked flints (Fig. 244) and are found in large numbers in caves and river terraces that were the resort of prehistoric man. Their intrinsic interest is enhanced by their number and variety, which compensates to some extent for the scarcity of fossil skeletons in the study of the phylogeny and distribution of early man.

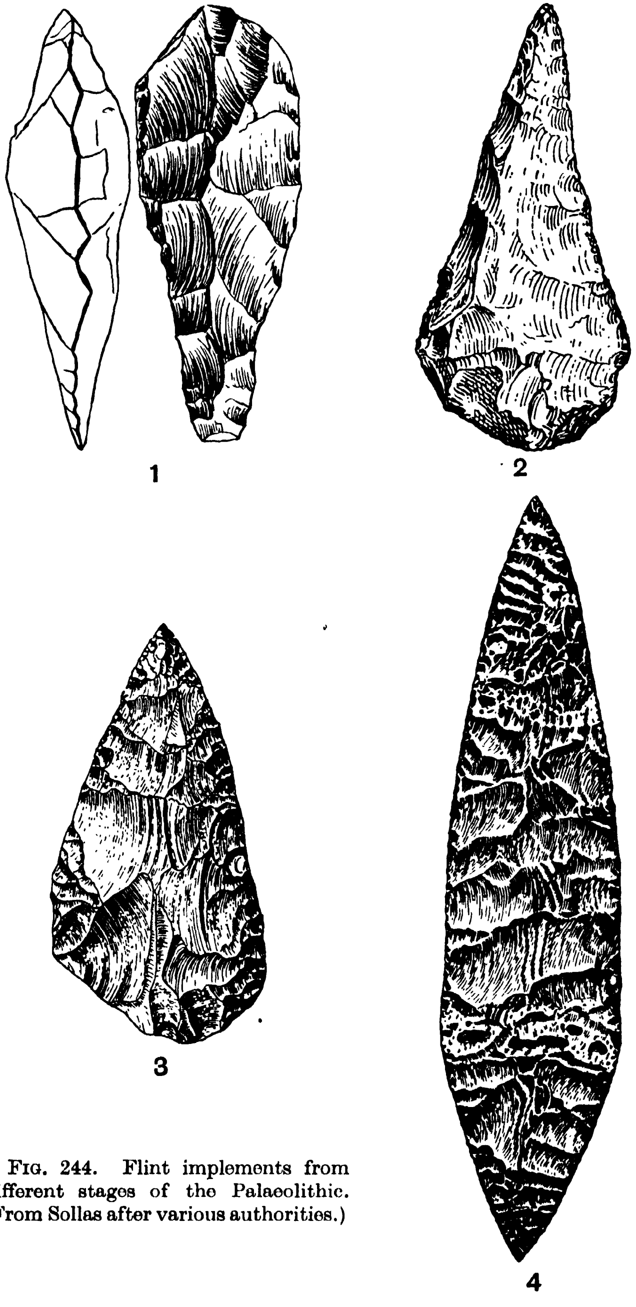


Fig. 244. Flint implements from different stages of the Palaeolithic. (From Sollas after various authorities.)

CHAPTER LV

PLANTAE: PHYLA THALLOPHYTA AND BRYOPHYTA

ANIMALS derive their energy and build up their tissues by feeding on plants or on other animals. They cannot use directly the simpler inorganic substances. Typical plants, on the other hand, with the aid of a green pigment, chlorophyll, by which they absorb light energy, transform water and carbon dioxide into substances such as sugar, starch, cellulose and lignin. The plant is also able to synthesize from these compounds, and from the nitrogen absorbed from the soil, highly complex organic substances such as proteins. Although this physiological distinction between plants and animals is valid for the higher forms it is not absolute among the simpler organisms. For example, Fungi and Bacteria are plants, although they have no chlorophyll. Again there are forms that might go into either category, like certain flagellates which are active after the manner of animals but possess chlorophyll, with the aid of which they can nourish themselves on the simpler compounds. All unicellular organisms, however, are not of this ambiguous type. Most of the Protozoa are quite definitely and obviously animals, and similarly a host of unicellular motile organisms are just as definitely plants, such as single-celled forms of the primitive Green Algae.

In animals the primary classification into phyla is determined by structural similarity, but in plants it is based primarily on the nature of the reproductive structures and processes, and only secondarily on the structure of vegetative characters. Four major groups, or phyla, may be recognised:

Thallophyta (seaweeds, Fungi, etc.)
Bryophyta (mosses and liverworts) } Spore plants (Cryptogamae)
Pteridophyta (ferns, horsetails, etc.)
Spermatophyta—seed plants (Phanerogamae)

Various circumstances contribute to restrict the geological utility of plants. The effective establishment of a land flora and the contingent evolution of plant structures that fossilize readily did not take place until Silurian times, and, therefore, in the Lower Palaeozoic rocks practically the only records of plants are sporadic fossils of lime-secreting seaweeds. Leaves, which are by far the commonest plant fossils, are not always reliable guides to affinity. Fossils of land plants are sparse in marine sediments, where they usually occur, if at all, as drifted foliage. Where they are found commonly, as in swamp and fresh-water deposits, the favourable conditions are often locally restricted. In the Coal Measures, however, and in the later continental deposits of Gondwanaland, favourable conditions for the preservation of plant tissues were widespread and enable the fossil flora of these formations to be used with special effectiveness in problems of chronology and palaeogeographic reconstruction.

Coming to more recent times the leading types of modern plants extend right back to Upper Cretaceous with little change, and some go still farther. Contrast this state of affairs with the faunal transformation in the same interval. Ammonites disappeared, belemnites were reduced to a few insignificant and unrepresentative relicts, and lamellibranchs and gastropods achieved dominance in the marine invertebrate faunas of Kainozoic. Among the vertebrates the dinosaurs and the giant marine and flying reptiles disappeared, and the mammals and birds prevailed in their respective spheres. The modern floras, however, have made some changes of distribution that reflect striking modifications of geographical and climatological conditions at different times and in different regions.

One difficulty in the interpretation of the plant record arises from the fact that fossils of plants are commonly detached parts such as leaves, seeds, or stems. It is not always possible to determine the relationships of these parts when they are first described, and the necessity of assigning them to various ‘ form-genera ’ often results in taxonomic complications. Thus the cones of the lycopod genera *Lepidodendron, Lepidophloios* and *Bothrodendron* are assigned to various species of one form-genus, *Lepidostrobus.* The following is an example of even greater taxonomic complexity: the frond called originally *Sphenopteris hoeninghausi* has been found attached to a stem called *Lyginopteris oldhamii.* Seeds preserved in coal-balls and called *Laginostoma lomaxi* have been proved to belong to *Lyginopteris* plants. They had previously been obtained in impression form and called *Calymmatotheca*; therefore the correct name for the plant is *Calymmatotheca hoeninghausi.*

PHYLUM THALLOPHYTA

In this somewhat heterogeneous phylum are included the simplest plants, those in which there is little or no differentiation of organs like stems and leaves. Many of them are unicellular, but the higher seaweeds form large and complex plants. Reproduction takes place by releasing special cells called spores, each capable of developing directly into an independent plant; or reproduction may be sexual, the thallophyte releasing male and female cells, each of the latter giving rise to a new plant if fertilized by conjugation with a male cell from the parent or other plant.

It is convenient to recognise three major groups of Thallophyta. The members of the first group have chlorophyll and comprise the classes CYANOPHYCEAE (Blue-Green Algae), ALGAE (seaweeds), and DIATOMEAE (diatoms). In the Blue-Green Algae the cells may be single or arranged in chains or filaments which are frequently enclosed in a tough protective sheath. It is well known that the Blue-Green Algae in particular are often instrumental in causing the deposition of calcium carbonate from natural waters. To such activities may be due some of the structures in limestones such as ooliths and pisoliths and some of the cryptic ' fossils ' of the pre-Cambrian, although in other cases such structures are doubtless of inorganic origin.

In some Algae, particularly the groups Chlorophyceae (Green Algae) and Rhodophyceae (Red Algae), the cellular framework of the body becomes encrusted with calcium carbonate. The nodular masses of *Lithothamnium*, resembling lumps of coral and widely distributed at the present day, may be cited as an example. Such calcareous seaweeds fossilize readily, and furnish most of the plant-fossils of the Lower Palaeozoic. *Girvanella,* which occurs fossil in the Girvan district of Scotland in the Ordovician, and at higher horizons elsewhere, being especially abundant in Carboniferous and Jurassic oolites, formed tangled masses of worm-like tubes in nodules (Fig. 245).

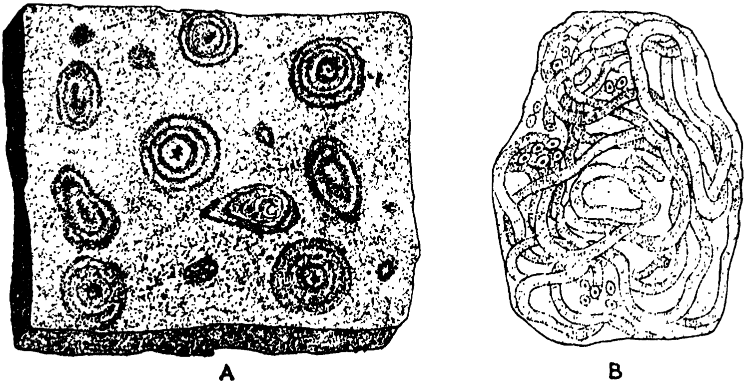


FIG. 245. *Girvanella.* (After Nicholson.)

A. Piece of limestone showing nodules of *Girvanella.*
B. Section of a nodule, much enlarged, showing the vermiform tubes.

Ortonella and *Mitcheldeania* are nodular forms with radial tubules that are common at certain horizons in the British Carboniferous.

Important as rock-formers are the diatoms (Fig. 246), tiny plants that secrete siliceous coverings consisting of two closely fitting valves. The majority are marine plankton. They live in millions near the surface of the ocean, and their skeletons, like those of the planktonic Protozoa, sink to the bottom to form oozes. Diatom ooze forms an almost continuous band just north of the Antarctic Continent, and also covers a smaller area on the floor of the North Pacific (Fig. 17). Upraised and consolidated diatom oozes are known, but no well authenticated examples of these algae have been obtained from pre-Jurassic rocks.

The second major group of thallophytes, the FUNGI, have no chlorophyll and cannot synthesize inorganic compounds. Some are parasitic on other plants or on animals. Others live on the products of organic decay. The Fungi (moulds, toadstools, etc.) form masses of branching threads, the mycelium, which penetrate dead organic material or a living host on which the fungus is parasitic. A familiar fungus is the mushroom, the spore-bearing portion of which is edible. Fungi, owing to their perishable structure, are rare as fossils, but mycelial threads have been found penetrating both plant and animal fossils and several forms have been described from the silicified Devonian peat-bog of Rhynie (see p. 359).

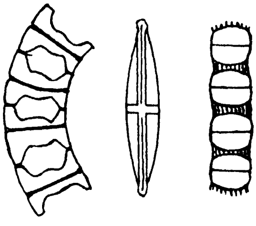


FIG. 246. Some Recent diatoms. (After Murray.)

The BACTERIA constitute the third group of thallophytes. They are microscopic bodies extremely simple in external form and are still lower in the scale of life than the Blue-Green Algae. They tend to assume rod-like, spherical or curved forms (Fig. 247), and may have lashing flagella for propulsion, or may be joined together in clusters or chains of varying shape. Bacteria may be claimed as plants. They possess no chlorophyll, and are especially remarkable for the physiological diversity which gives them their peculiar place in the economy of life. It is well known that some Bacteria deposit calcareous and ferric substances as end-products of their metabolism, and therefore they have a special interest to geologists as the probable

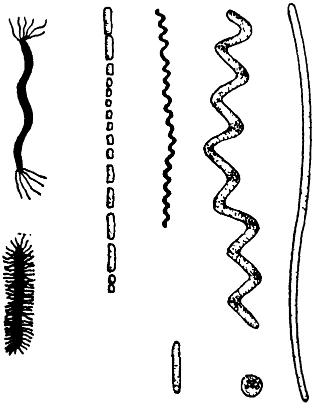


FIG. 247. Some examples of bacteria.

source of many limestones, dolomites and iron ores. They occur occasionally as recognisable fossils—*e.g.* in the Rhynie chert of Aberdeenshire (see p. 359).

PHYLUM BRYOPHYTA

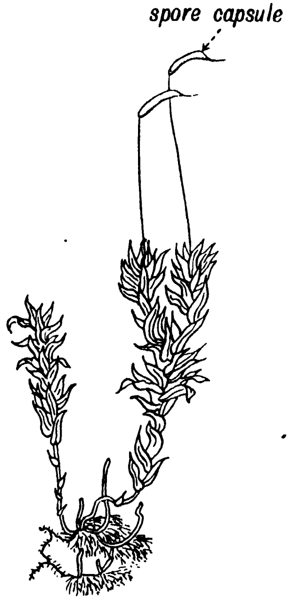


FIG. 248. Leafy moss gametophyte with two sporophytes. (Modified after Wells, Huxley and Wells.)

The conditions that forced the lung-fish to colonize the land about the time of the Caledonian Revolution are thought by some to have led to the evolution of a type of plant adapted to land conditions. It is possible that land plants may have evolved from some algal stock, but critical evidence is lacking. The adaptation of aquatic plants to terrestrial life involved the development of an epidermis which prevented excessive evaporation of water, rooting hairs (rhizoids) to absorb water and mineral salts from the soil, and the investment of spores with a resistant cuticle. This phase of plant evolution is represented in the modern flora by the mosses and liverworts (Bryophyta). The reproductive arrangements of the Bryophyta show an advance on those of the Thallophyta. A spore-bearing generation (sporophyte), consisting of tiny capsules on slender stalks (Fig. 248), alternates with and is parasitic upon a green sexual plant (gametophyte) which produces the male and female sexual cells (gametes). Alternation of sporophyte and gametophyte generations found in some Algae is characteristic of all the higher plants. Both mosses and liverworts have been recognised in rocks as old as Carboniferous, but they are not common fossils, owing to their unsuitability for preservation.

CHAPTER LVI

PLANTAE: PHYLUM PTERIDOPHYTA

THE size of the early terrestrial plants, like that of their modern analogues, the bryophytes, may have been restricted by the mechanical limitations of their primitive cellular structure. Increase in size and consequent potentiality for more perfect adaptation to terrestrial life involved the provision of some structural device as a substitute for the support given by water, and of a conducting system for the transport of nutrient fluids to all parts of the plant-body. Both ends were achieved by arranging certain cells within the plant as lignified tubes bound together in bundles (Fig. 249). This type of

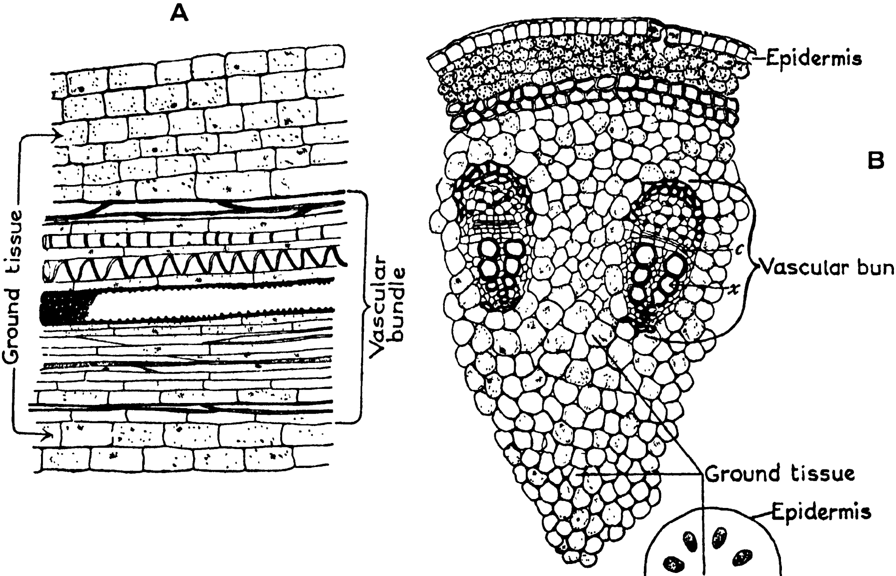


FIG. 249. Tissues in a stem of a flowering plant. Magnified. (After Stopes.)
A. Longitudinal section. B. Transverse section.

structure is described as vascular. The pteridophytes are the plants which achieved this further step in adaptation to terrestrial life. Their commonest representatives at the present time are the ferns. The pteridophytes are sometimes called the vascular cryptogams, *i.e.* vascular plants that reproduce without flowers and seeds, and have lignified water-conducting tissue, in contrast to the non-vascular cryptogams, thallophytes and bryophytes, which lack the specialized conducting tissue. In the ferns the conspicuous leafy plant is the spore-bearing generation. The plant that develops from a spore is not a leaf-bearing fern, but a flat, green thallus, called the prothallus (Fig. 250), which is anchored to the soil by rhizoids and bears male and female reproductive organs. Union of gametes produced by the prothallus gives rise in turn to a spore-bearing leafy fern. The prothallus is so inconspicuous as to be unknown to most people. In the mosses the converse is true, the conspicuous leafy phase is the sexual generation. The distinction is important, because it illustrates a tendency in the reproductive processes of higher plants to subordinate the size and duration of the sexual phase to the vegetative aspects of the plant.

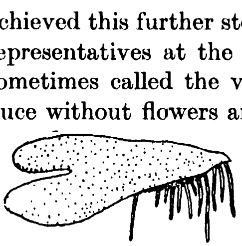


FIG. 250. Prothallus of a fern. (After Wells, Huxley and Wells.)

The following are the classes of Pteridophyta that are of most interest to the student of fossils :

Psilophytinae (primitive pteridophytes of the Devonian)
Lycopodiinae (club-mosses)
Articulatae { Equisetinae (horsetails)
Sphenophyllineae (extinct pteridophytes of the Palaeozoic)
Filicinae (ferns)

We shall discuss these classes as nearly as possible in the chronological order of their appearance as fossils, in order to sketch roughly the growth and differentiation of the land flora.

The date of the migration to land and the manner of its accomplishment are unknown, although generalizations about both may be inferred from the nature of geographical and physical conditions towards the end of the Lower Palaeozoic (see p. 322). Fossils of undoubted land plants with spores and lignified water-conducting tissues have been found in Australia, associated with Lower Ludlovian graptolites. *Baragwanathia* (Fig. 251), the most completely known of these Australian Silurian plants, had stout, dichotomously branched shoots clothed with long, spirally arranged and vascular leaves that were lax and not stiff or spine-like. Kidney-shaped sporangia occurred in definite zones among the leaf-bases. The shape and position of the sporangia suggest affinity to the club-moss *Lycopodium*, but the structure of the vascular tissue points to close connection with the characteristic plants of the Lower Devonian flora, the PSILOPHYTINAE (Fig. 252), which are rootless plants with branches that occasionally fork and may be smooth or bear spinous emergences.

The Middle Devonian flora did not differ essentially from that of the Lower Devonian. The Psilophytinae were still the most important constituent of the land flora, and our knowledge of their internal structure was greatly extended by the beautifully preserved remains of the genera *Rhynia*, *Hornea* and *Asteroxylon* (Fig. 253) obtained from a silicified Middle Devonian peat bog at Rhynie in Aberdeenshire. Apart from some primitive traits, the organization of the tissues was surprisingly modern. Because the spore-bearing generation in *Rhynia* and *Hornea* was a vascular plant these genera have been assigned to the Pteridophyta by Dr. Kidston and Professor Lang, who described this unique flora in a series of memoirs which, although completed so recently as 1921, are already classics of palaeobotany. These genera show a remarkable combination of characters, such as a thallus-like appearance of the stem, which yet possessed vascular tissues, a stout cuticle, and stomata, and structural resemblance of the sporangia on the tips of the thallus-branches of *Hornea* to the spore-capsules of certain mosses. In

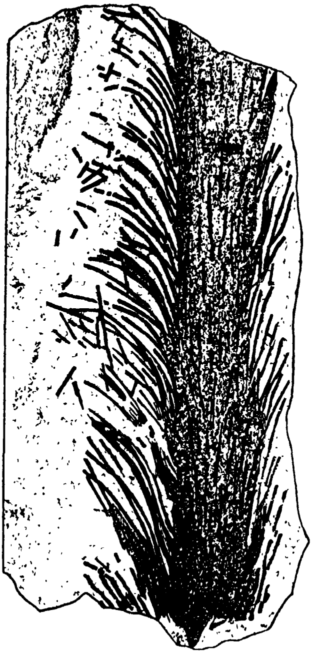


FIG. 251. *Baragwanathia*. Portion of a leafy shoot. (After Lang and Cookson.)

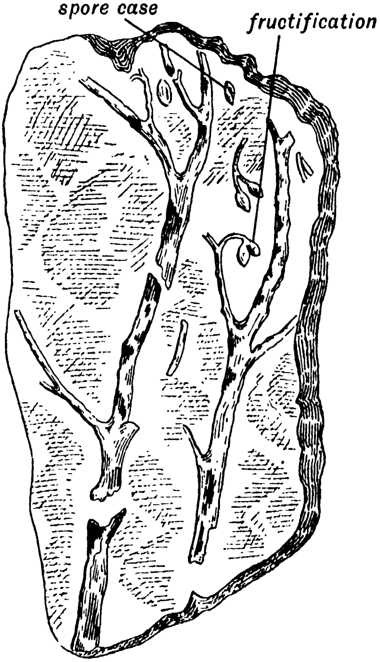


FIG. 252. *Psilophyton*. (After Kidston.)

Asteroxylon, which stood somewhat apart from the other two genera, the stem was clothed with small leaves, a habit that recalls *Baragwanathia* and the club-mosses (see below), but the leaves of *Asteroxylon* were not vascular to their extremities and were shorter than in *Baragwanathia*. The associated fructifications, which have never been found in actual connection with the plant, are somewhat like the sporangia of certain Carboniferous ferns.

Before the end of the Middle Devonian the primitive LYCOPODIINAE appeared, the earlier Devonian Psilophytinae disappearing after the Middle Devonian. The Lycopodiinae are represented in the modern flora by the so-called club-mosses, like *Lycopodium* (Fig. 254A), *Selaginella* (Fig. 254B) and *Isoëtes* (Fig. 254C), in which the stems are covered with relatively small, spirally disposed and closely crowded leaves. The *Lycopodium* type of plant was represented in the Silurian by *Baragwanathia* ; *Selaginella* and *Isoëtes* are undoubtedly the humble relicts of a stock that attained its full vigour in the Carboniferous, and contributed 100-foot trees to the forests of that period. The genera *Lepidodendron* and *Sigillaria* are usually taken as representatives of the large Carboniferous lycopods. In *Lepidodendron* (Fig. 255) the stem was tall and produced branches often by dichotomous forking. As in *Lycopodium*, the stem and branches of *Lepidodendron* were densely clothed with spirally arranged leaves. When these leaves were shed their bases remained attached to the plant, and fragments of stem and branches showing the convex, spirally arranged, rhombic leaf-cushions are the commonest fossils of *Lepidodendron*. All the parts, however, are represented by fossils—trunks

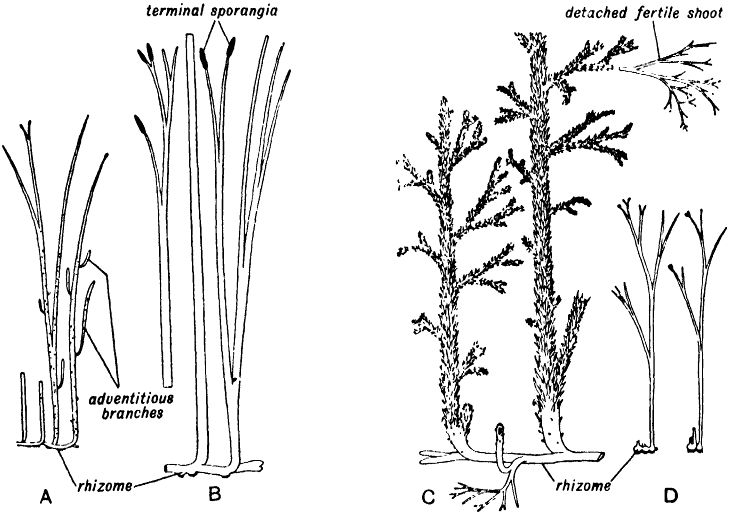


FIG. 253. The Rhynie plants. (After Kidston and Lang.)
A and B. *Rhynia*. C. *Asteroxylon*. D. *Hornea*.

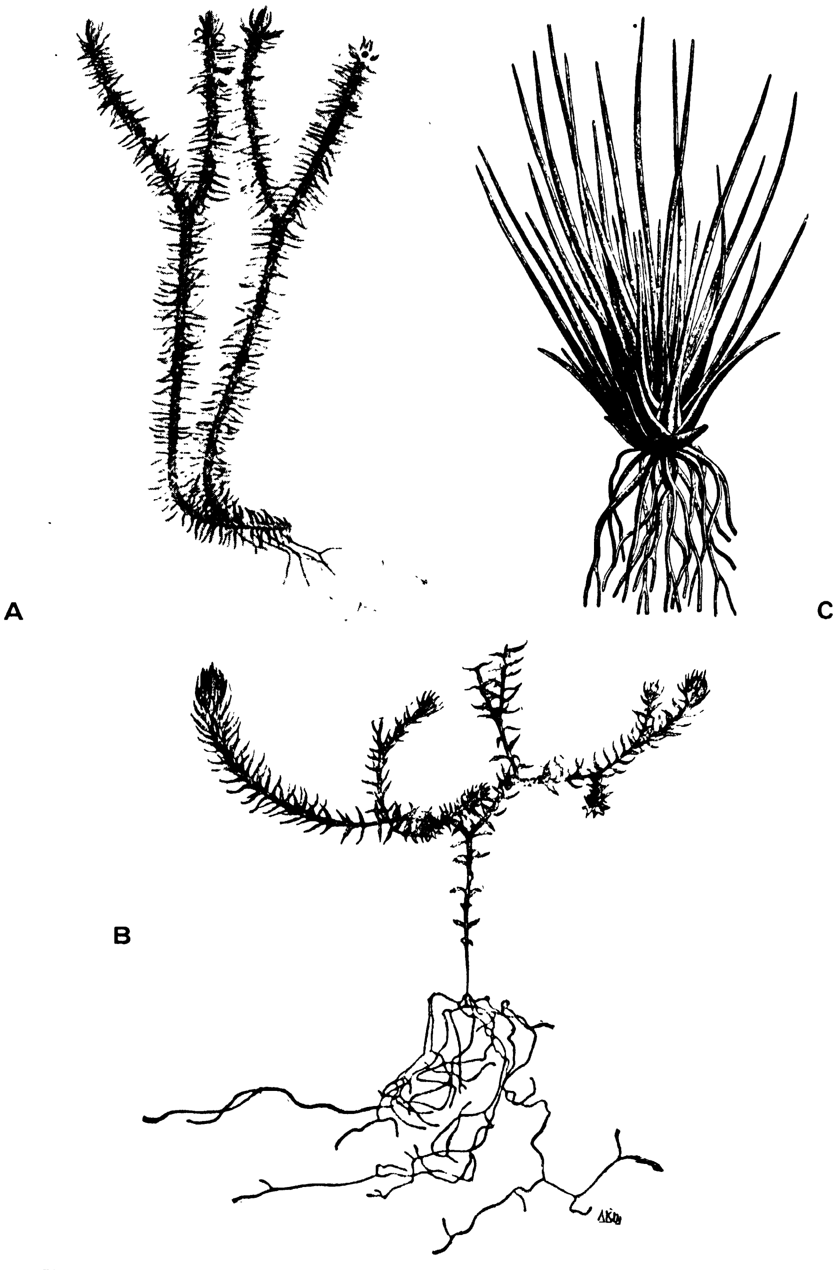


Fig. 254. Modern lycopods. (A and B after Bower; C after Rabenhorst.)

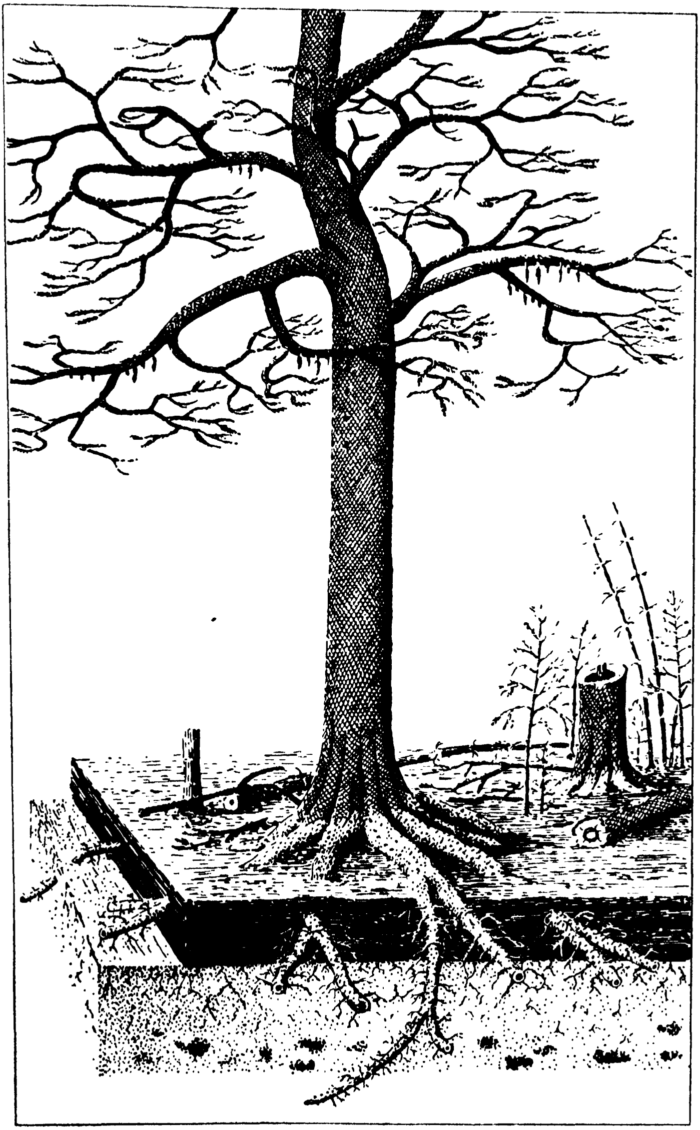


FIG. 255. *Lepidodendron.* (After Walton, Geol. Surv. illustration.)

showing the vascular structure, leaves and fruits, as well as the stems and branches just described. Grass-like or lanceolate lycopod leaves of the Carboniferous which cannot be assigned to the parent plant are referred to the form-genera *Lepidophyllum* and *Sigillariophyllum*. The cones, which are referred to the form-genus *Lepidostrobus*, indicate the affinity of *Lepidodendron* to the *Selaginella* type of club-moss. They were usually situated at the ends of the smaller leafy branches and took the form of cylindrical cones with crowded bracts (sporophylls) spirally arranged round an axis, as in living lycopods. Each bract carried a spore-case on its upper surface. Like the modern *Selaginella* most, if not all, of the Palaeozoic arborescent lycopods were heterosporous, that is, they produced spores of two sizes, the larger (megaspores) giving rise to female prothalli and the smaller (microspores) to male prothalli. Where both kinds of spores were produced on the same cone the larger occurred on the lower part of the cone and the smaller on the upper part. Both microspores and megaspores of Carboniferous pteridophytes varied greatly in character (Fig. 256) and are preserved in large numbers in coal. They can be isolated for

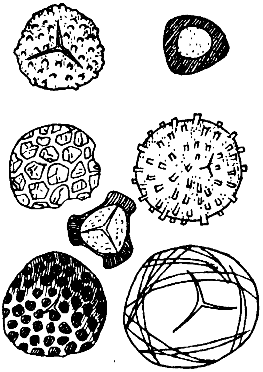


Fig. 256. Some Coal Measures pteridophyte microspores. Highly magnified. (After Raistrick.)

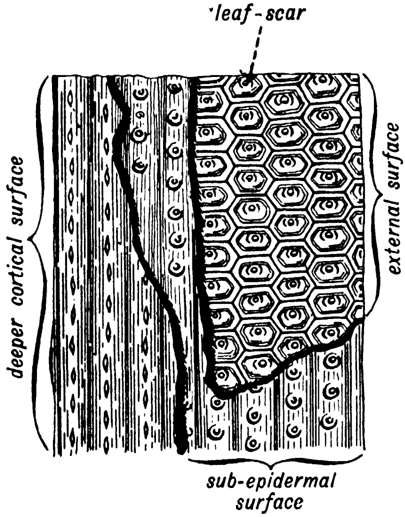


Fig. 257. *Sigillaria*. Portion of stem, showing successive stages of decortication. (After Schimper.)

study from their coaly matrix by special techniques, and although it is impossible to assign the various kinds to their parent species, empirical study of the spore-assemblages in coals from different stratigraphical horizons has demonstrated their value in the correlation of coal-seams over limited areas.

Large trees require to be firmly rooted, and in *Lepidodendron* this was achieved by spreading underground branches which bifurcated like the subaerial branches and carried numerous small appendages or rootlets. When the rootlets themselves are not preserved—a common condition—the scars of their attachment are seen as small circular pits or depressions on the surface of the underground branch. These root-like organs are referred to the form-genus *Stigmaria,* and belonged not only to *Lepidodendron* but also to other lycopod genera such as *Sigillaria,* most species of which differ from *Lepidodendron* in having their leaf-cushions arranged in regular vertical rows (Fig. 257). *Stigmaria* is the commonest fossil of the Coal Measures, but has no stratigraphical value.

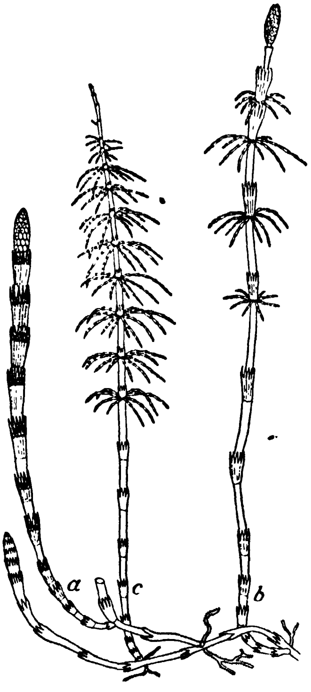
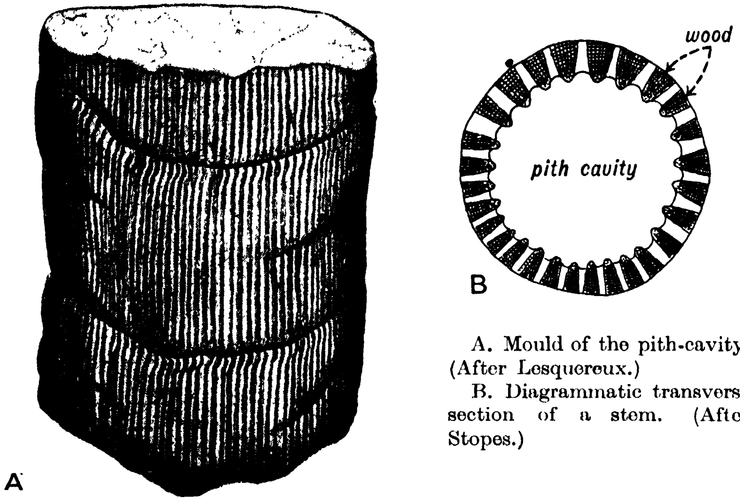


FIG. 258. *Equisetum.* (After Duval-Jouve.)

The Equisetinae and Sphenophyllineae were articulate plants, with jointed stems and branches. Leaves occurred in whorls at the joints (nodes), and the internodular portions of stem and branches were bare. The common 'horsetails' (*Equisetum,* Fig. 258) are modern EQUISETINAE. Primitive Articulatae appeared in the Middle Devonian, and like the lycopods attained their acme in the Carboniferous forests. The commonest fossils of the Palaeozoic Equisetinae belong to *Calamites,* a genus that produced trees up to 100 feet in height. Internal moulds of the hollow stem, marked transversely with the more or less circular nodes, and longitudinally with ridges and furrows, are often found (Fig. 259A). The furrows are the impressions of wedges of wood that projected into the pith-cavity of the stem (Fig. 259B), and this system of furrows and ridges in the internal mould of *Calamites* is therefore not homologous with the external ribbing on the stem of a recent horsetail. The outer surface of the calamitean stem is not commonly preserved, but it was either smooth or striated. The cones of *Calamites* (Fig. 260) have been described under various names. They were rarely heterosporous and consisted of alternating whorls of sterile bracts and fertile sporangiophores. *Calamites* became extinct in the Permian. The genus *Annularia* (Fig. 261), with its whorls of small, lanceolate leaves, represents the foliage and smaller branches of some types of *Calamites.*



A. Mould of the pith-cavity. (After Lesquereux.)

B. Diagrammatic transverse section of a stem. (After Stopes.)

FIG. 259. *Calamites.*

The SPHENOPHYLLINEAE (Fig. 262 A and B) were small articulate plants, possibly climbers, with solid, ribbed stems. Whorled leaves occurred in multiples of three, those of the Devonian and Lower Carboniferous being narrow and finely divided, those of the Upper Carboniferous characteristically wedge-shaped, often lobate ; different types of leaf may be observed on one plant. The cones were long and narrow, but the bases of the numerous bracts fused to form a collar round the axis. The plants were probably all homosporous. The Sphenophyllineae ranged from Devonian to Permian.

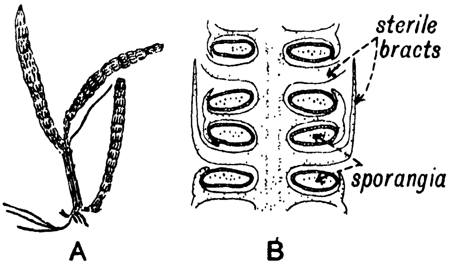


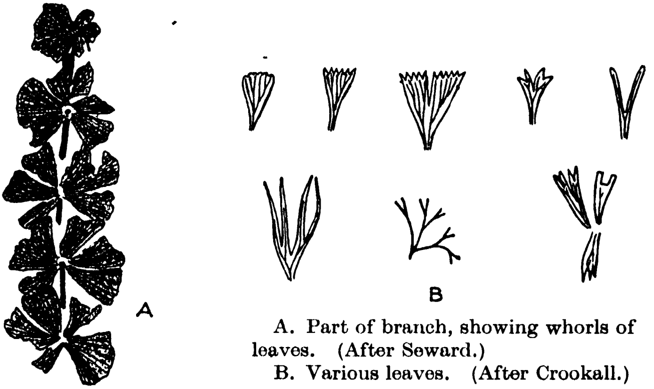
FIG. 260.

A. *Calamostachys*, a fertile calamitean shoot. (After Seward.)

B. Diagrammatic section of a calamitean cone. (After Stopes.)

The leaves (fronds) of ferns (Filicinae) are so common in favourable situations at the present time that a generalized description is hardly necessary here. The spores are borne in spore sacs on the foliage fronds or on fronds of special type. The earliest known fern, *Asteropteris*, is a fragment of petrified stem from the Upper Devonian of New York State. The true ferns of the Upper Palaeozoic showed a wide range of reproductive and vegetative characters. Many belonged to groups now extinct, but certain groups have survived to the present day. They were subordinate in numbers to certain seed-plants with fern-like leaves, the Pteridospermae (see p. 369).

FIG. 261. *Annularia*. (After Walton.)



A. Part of branch, showing whorls of leaves. (After Seward.)
B. Various leaves. (After Crookall.)

FIG. 262. *Sphenophyllum*.

CHAPTER LVII

PLANTAE : PHYLUM SPERMATOPHYTA

In the purely vegetative aspects of their existence the Pteridophyta adapted themselves completely to life on land, but, as in the Bryophyta, they remained dependent upon water for the union of the male and female reproductive cells. The seed-plants, Spermatophyta (also called Phanerogamae), achieved complete emancipation from water in their reproductive processes.

The reproductive process of the seed-plant is complicated, but a summary is desirable in order to indicate the nature of the seed, which, as implied in the name Spermatophyta, is an integral part of the reproductive system of the higher plants ; it is necessary also to demonstrate the relationship of this mechanism to the analogous processes in the lower plants in order to obtain an elementary understanding of the primitive seed-plants of the Upper Palaeozoic.

The Spermatophyta are divided into two classes—Gymnospermae and Angiospermae. The former, which include the conifers, are more primitive, but we shall describe the process in the latter class, because it includes all the common flowering plants, and most readers are probably familiar with the main structures of the flower (Fig. 263) which is the part of the plant that is concerned in reproduction.

When an angiospermous seed is planted in suitable conditions it gives rise to a plant with root, stem, leaves and flowers. This plant corresponds to the spore-bearing heterosporous fern. It has ovules, each containing a megaspore, and pollen sacs that enclose the microspores (pollen grains). The various parts of the flower (petals, stamens, pistil, etc.) are modified leaves, although recently doubts have been cast on this classical interpretation of their homology. Within the coloured corolla of a bisexual flower the pollen-bearing stamens (microsporophylls) surround the pistil, which contains the ovules in a closed ovary. When a pollen grain, which contains two or three cells, is deposited by the agency of wind or insect on the stigma (extremity of the pistil), it begins to grow, developing a tube which pierces the stigma and penetrates the ovule. That is, the growing pollen grain is a little plant corresponding to the male prothallus of a heterosporous lycopod. The ovule consists of a single megaspore surrounded by protective layers, and inside the megaspore is the female prothallus. We have seen that one of the cells

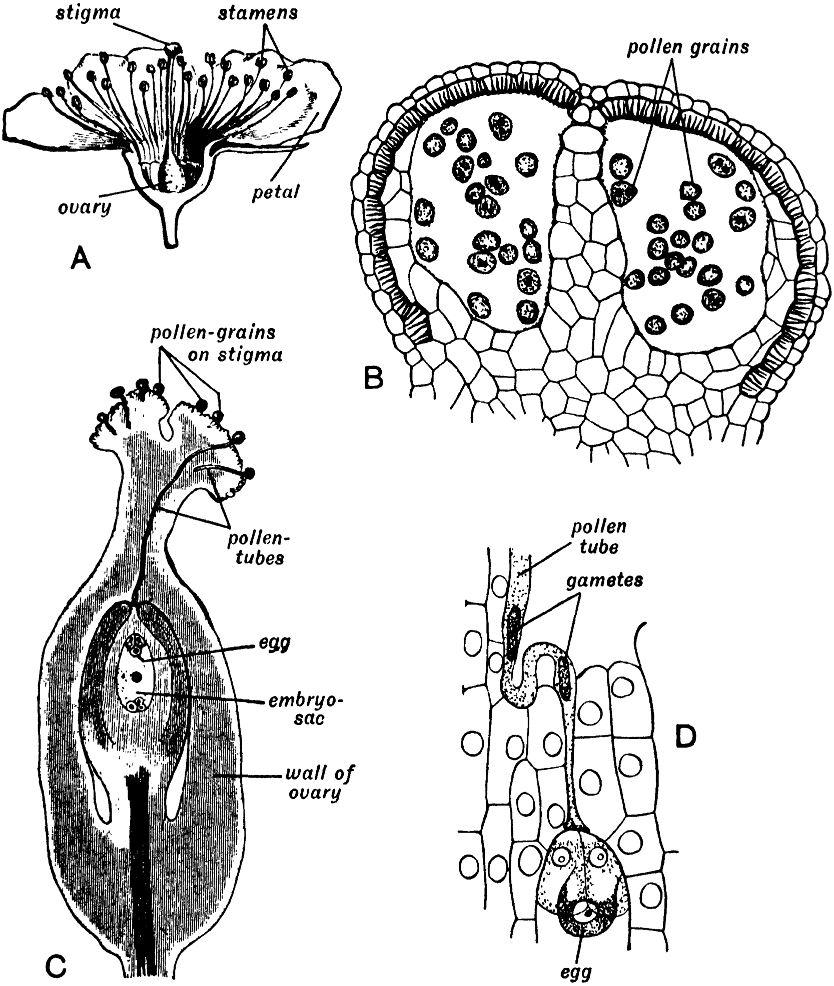


FIG. 263. Flower and fertilization.

A. Vertical section of flower of the peach. (After Figuier.)

B. Section showing pollen grains in two pollen sacs. Much enlarged. (After Bower.)

C. Ovary of *Polygonum* at time of fertilization, showing pollen grains germinating on stigma and sending pollen tube to the ovules. Enlarged. (After Strasburger.)

D. Gametes descending the pollen tube, which has penetrated the tissues to reach the ovule. (After Strasburger.)

derived from the pollen grain developed into a tube that descended the stigma, penetrating the ovule and finally the megaspore. Down this tube the remaining two cells (the male gametes) descend into the megaspore (embryo sac) to the female prothallus and one of them conjugates with the female gamete. The fertilized cell begins at once to grow, nourished by the surrounding tissues. The resulting embryo or germ has a root and seedling leaves (cotyledons). At this stage growth ceases until the ovule, or seed * as it may now be called, is transported to a soil favourable for its development into the flowering (*i.e.* pollen and ovule-bearing) plant. In some angiosperms pollen and ovules are borne in separate flowers or on different plants. Catkins, for instance those of the hazel, are well-known examples of groups of pollen flowers, the female flowers being distinguished from the ordinary hazel leaf-buds only by the tufts of crimson stigmas at their tips. Thus in the life cycle of the higher plants, as in the ferns and mosses, there is an alternation of gametophyte (sexual) and sporophyte (asexual) generations. The former, however, although as important as in the lower plants, is so inconspicuous that it is passed entirely within the flower of the sporophyte.

In the GYMNOSPERMS the cones correspond to the flowers of the angiosperms, and bear ovules and pollen. The ovules are naked, *i.e.* they are not enclosed as in the angiosperms in an ovary formed by the megasporophylls. The pollen grain is often lodged directly on the ovule, and the pollen tube is usually shorter than in the angiosperms.

The Carboniferous rocks contain an abundance of fossil plants with fern-like leaves that were thought to be ferns until true seeds were found attached to the leaves. This group of Palaeozoic plants is known as the Pteridospermae (seed ferns) or Cycadofilicales (cycad-like ferns). It is possible that in some stock of Palaeozoic heterosporous ferns the megaspores enlarged and, instead of being shed, remained within the megasporangium, which thus became a seed. An analogous occurrence is known, not in a Palaeozoic fern, but in *Lepidocarpon*, a Carboniferous fructification that probably belonged to one of the Lepidodendreae. In *Lepidocarpon* only a single megaspore in each sporangium came to maturity, and this spore was not shed, but developed its

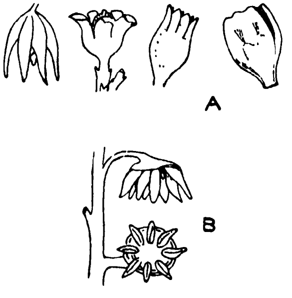


FIG. 264.

A. Some cupuliferous seeds of pteridosperms. (After Hamshaw Thomas.)

B. *Crossotheca*. (After Kidston.)

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* The common bean seed is a familiar example, in which the parts of the germ are readily recognised. The two fleshy lobes within the tough seed-coat are the cotyledons. The form and proportions of the seed and of the embryo and its parts vary in different plants.

prothallus within the sporangium wall. Thus a primitive type of seed was formed. *Lepidocarpon*, of course, had no direct connection with pteridosperms.

Stems like that described by Hugh Miller from Cromarty and now known as *Palaeopitys* suggest that gymnospermous plants may have existed in the Middle Devonian. The seeds of some Palaeozoic pteridosperms were partially enclosed in a cupule (Fig. 264A) like a hazel nut in its husk and were borne on a frond or leaf. In some of the later Palaeozoic pteridosperms non-cupuliferous seeds were borne directly on the upper surfaces of fronds which are indistinguishable from sterile fronds of the same plant.

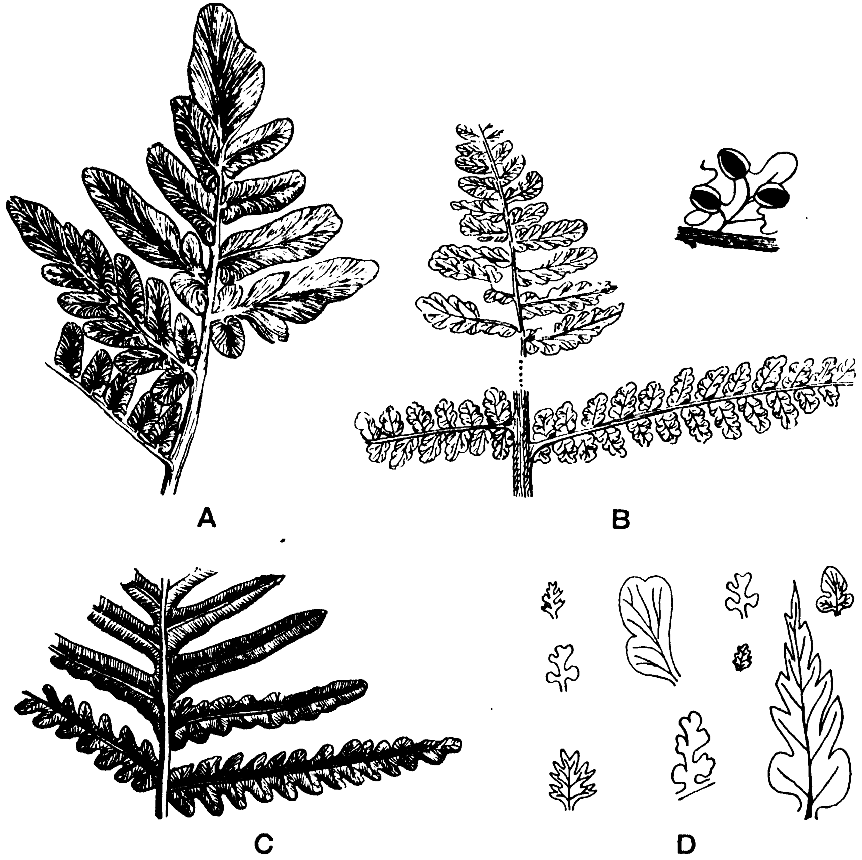

FIG. 265. Fronds of Carboniferous pteridosperms.

A. *Neuropteris.* (After Geikie.)
B. *Pecopteris.* Frond and pinnule with seeds. (After Seward.)
C. *Alethopteris.* (After Geikie.)
D. *Sphenopteris.* Various pinnules. (After Crookall.)

Many pollen-bearing structures of the pteridosperms had the type of construction exemplified by the well-known Carboniferous *Crossotheca*, which has been observed on fronds of *Pecopteris* type. In *Crossotheca* the pollen sacs were suspended in a fringe from a central disc (Fig. 264B). There were various modifications of this type of structure. The pteridosperms attained their acme in the Upper Carboniferous, forming a high proportion of the flora of the time, and declined gradually to extinction in the Jurassic. The fronds of the genera *Neuropteris* (Fig. 265A), certain species referred to *Pecopteris* (Fig. 265B), *Alethopteris* (Fig. 265C) and *Sphenopteris* (Fig. 265D) are common fossils of Carboniferous pteridosperms. Tongue-shaped leaves of later date, named *Glossopteris* (Fig. 266A and B) were almost certainly pteridospermous. *Glossopteris* and the associated assemblage of plants (for example, *Gangamopteris*, Fig. 266C) known as the *Glossopteris*-flora lived from late Carboniferous through Permian and Triassic times in the great continent of Gondwanaland (p. 441), in the deposits of which its leaves are fossilized in large numbers.

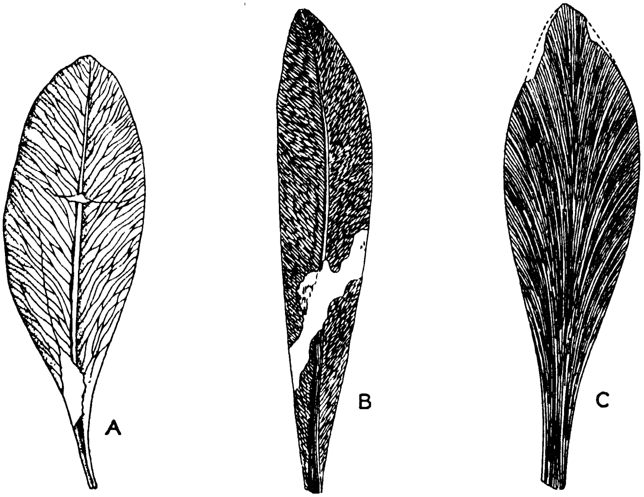

FIG. 266. Examples of the Glossopteris flora. (After Arber.)
A and B. *Glossopteris*. C. *Gangamopteris*.

Another group of Upper Palaeozoic gymnosperms, the Cordaitales, formed tall trees with slender stems, and a crown of branches with very long leaves. The sword-like, parallel-veined leaves of *Cordaites* (Fig. 267A), often 2 or 3 feet in length, are common fossils in the Carboniferous. The anatomy of the stem was similar to that of conifers, except in the large pith (moulds of the pith cavity, Fig. 267C, are called *Artisia*), but the male and female fructifications (Fig. 267B) took the form of catkins borne on special short branches.

The remaining gymnosperms include the Coniferales, Cycadales, and Ginkgoales; each of these groups has living representatives. The Coniferales are more familiar to inhabitants of the temperate regions than the cycads or *Ginkgo* (the Maidenhair Tree). Many of the well-known timber and ornamental trees are conifers. They are usually evergreen, with rigid needle-like or scaly leaves and male and female cones. Their origin is obscure, but, like the Ginkgoales, they may be related to the Cordaitales. The earliest genera were *Walchia* (Upper Carboniferous) and *Pseudovoltzia* (Permian). The leafy pinnate branches of *Walchia* (Fig. 268) occasionally bore terminal cones and resembled those of *Araucaria*, the monkey-puzzle tree or Norfolk Island Pine. *Pseudovoltzia* has a double cone-scale (Fig. 269) with (1) a pointed dorsal bract and (2) a ventral semeniferous portion having two small sterile lobes alternating with

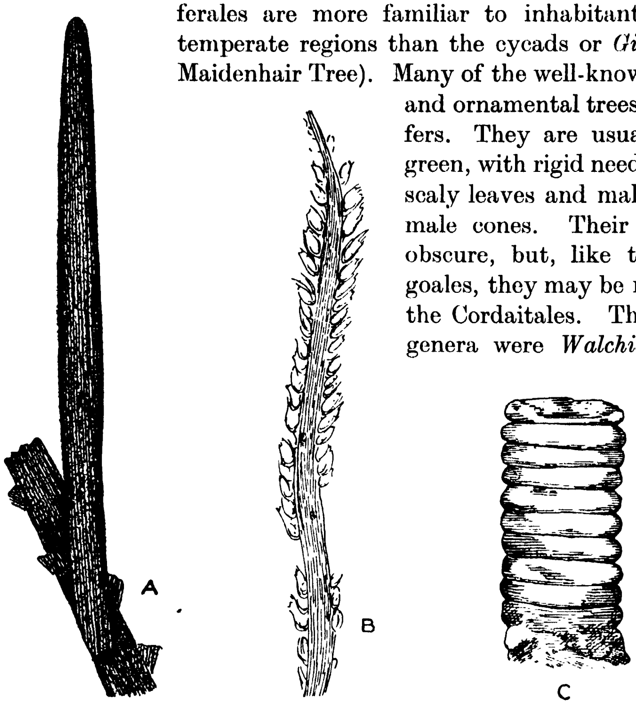

Fig. 267. Cordaitean fossils.

A. Leaf. (After Stopes.)
B. *Cordaianthus*, an ovulate shoot (After Seward.)
C. *Artisia*, mould of the pith cavity. Note constrictions due to transverse bands of tissue in the hollow stem. (After Stopes.)

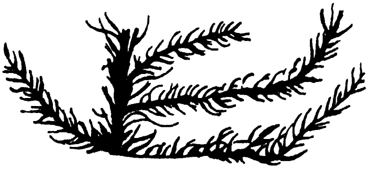

Fig. 268. *Walchia*. (After Weiss.)

three larger seed-bearing lobes. This assemblage of characters is distributed to-day among different families of conifers.

Conifers became prominent in the Mesozoic along with the cycadeoids and Ginkgoales, and the overwhelming predominance of these three groups in the land floras gave the Mesozoic its character as the Era of Gymnosperms.

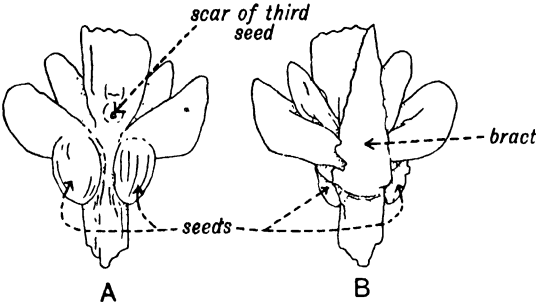

FIG. 269. Cone-scale of *Pseudovoltzia*. (After Walton.)
A. Ventral surface. B. Dorsal surface.

The modern cycads (Cycadaceae) often have a superficial resemblance to palms (they are sometimes miscalled sago-palms), and the few remaining genera have a wide distribution in warm countries. The stems are thick, columnar, covered with leaf-bases, and bear a crown of pinnate foliage (Fig. 270). The height does not exceed 60 feet, and sometimes the stems are dwarfed and subterranean. The sexes in living cycads are separate, so that individual plants are either pollen or ovule bearing. Except in the ovulate plant of *Cycas* the fructification is a large cone at the end of the stem, with scales carrying two ovules or, in the pollen-producing plant, about 1000 pollen-sacs. In the ovulate plant of *Cycas* no cone is formed; instead, special seed-leaves, smaller than the other leaves, are borne directly on the stem, a condition that occurred commonly among the Palaeozoic pteridosperms.

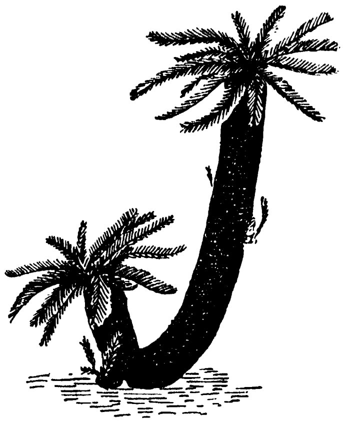

FIG. 270. *Cycas*. (After Stopes.)

Records of true Cycadaceae in the Mesozoic are scanty; the oldest fossils of the characteristic carpels (seed-leaves) come from the Rhaetic of Sweden. The common cycad-like trees of the Mesozoic belong to the extinct families Bennettiteae and Williamsonieae, which may be grouped together as cycadeoids. In their outward habit the Bennettiteae resembled the modern Cycadaceae, and the height of the very thick trunk rarely exceeded

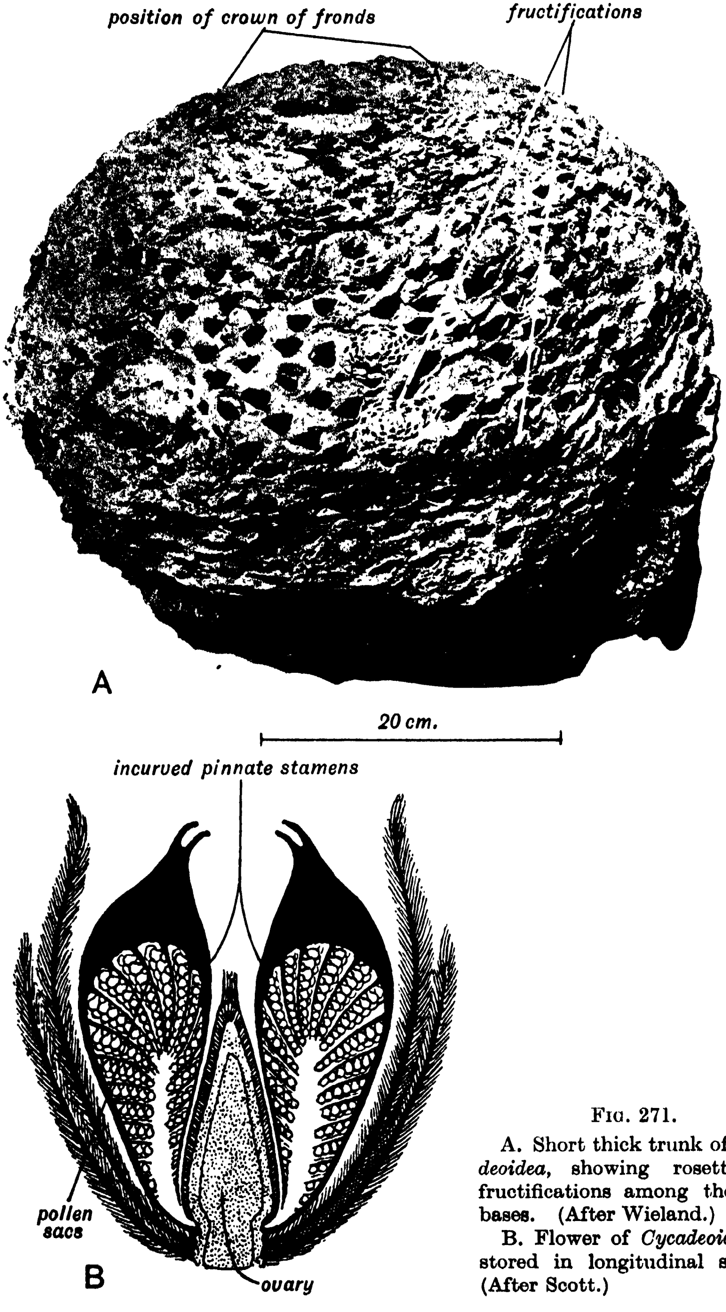

FIG. 271.

A. Short thick trunk of *Cycadeoidea*, showing rosette-like fructifications among the leaf-bases. (After Wieland.)

B. Flower of *Cycadeoidea* restored in longitudinal section. (After Scott.)

4 feet (Fig. 271A). They differed in having bisexual ' flowers ' consisting of bracts enclosing a ring of pinnate stamens that surrounded a central ovule-bearing cone (Fig. 271B). These flowers were situated on the stem, appearing like rosettes embedded among the leaf-bases (Fig. 271A). The Bennettiteae were numerous and widely distributed in Upper Jurassic and Lower Cretaceous, and have yielded some astonishingly well-preserved fossils. They did not, however, belong to the main cycad stock, but like the modern Cycadaceae, represented a terminal branch. The more ancient Williamsonieae, plants having pinnate foliage (Fig. 272B) of the cycad type and stalked fructifications, but with tall, slender, branching stems, were probably more nearly related to the main stock. Their fructifications were probably unisexual (Fig. 272B), and the stamens were not pinnate as in the Bennettiteae, the pollen sacs being typically borne on the main limb of the stamen. A small group of Rhaetic and Jurassic age, the Microflorae, which has been separated from the Williamsonieae, had bisexual flowers of cycad type in the forks of slender, branching stems of angiospermous habit (Figs. 273A and B). The narrow leaves were borne in clusters below the forks.

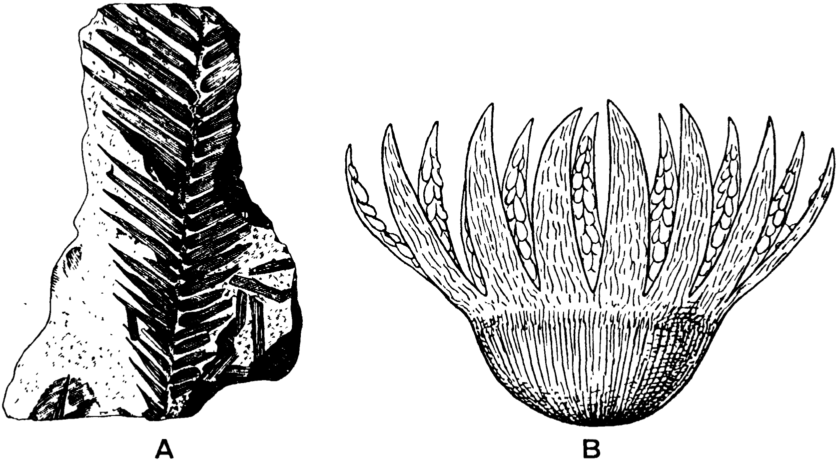

FIG. 272. *Williamsonia.*
A. Frond. (After Wieland.) B. Male flower. (After Nathorst.)

The Ginkgoales are represented at the present day by only a single species, the sacred Maidenhair Tree of the East (*Ginkgo biloba*), which is not known to grow now in the wild state. *Ginkgo* has a longer geological history than any living genus of plants. The leaves have a characteristic fan-like shape (Fig. 274), like those of the maidenhair fern, but larger. Foliage of this type occurs commonly and widely distributed in Mesozoic rocks, suggesting that the Ginkgoales were then at their acme and formed a conspicuous element in the Mesozoic floras. Unfortunately the fructifications of the fossil forms are not well known. The origin of the class is obscure, but it doubtless ranged back into Upper Palaeozoic, for Ginkgo-like leaves (*Saportaea*) are known from the Lower Permian of America and China.

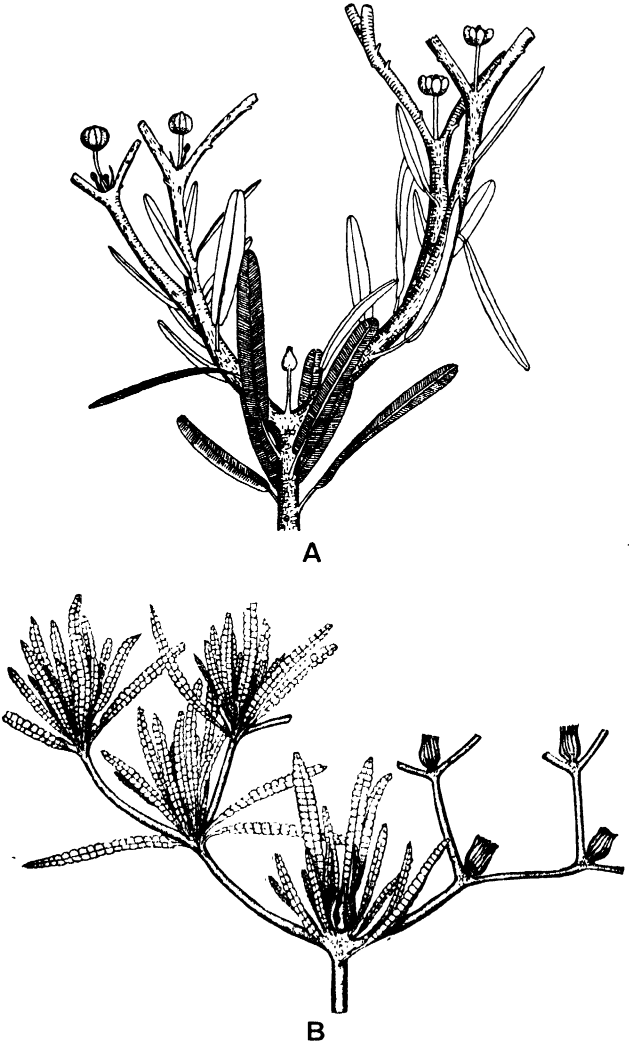

Fig. 273. Microflorae.

A. *Williamsoniella.* Restoration of part of a plant. (After Hamshaw Thomas.)

B. *Wielandiella.* Restoration showing forked stem, segmented leaves and flowers. (After Nathorst.)

In the cycads and *Ginkgo* the male cells are ciliated and swim from the pollen tube to the female prothallus inside the megaspore of the ovule through a fluid discharged from the bursting pollen tube. This mode of union recalls the limitation that binds the cryptogams in their fertilization, where water is essential for the mating of male and female cells. The conifers, like the angiosperms, dispense entirely with a fluid medium in fertilization and bring the male cells into direct contact with the ovule by means of the pollen tube.

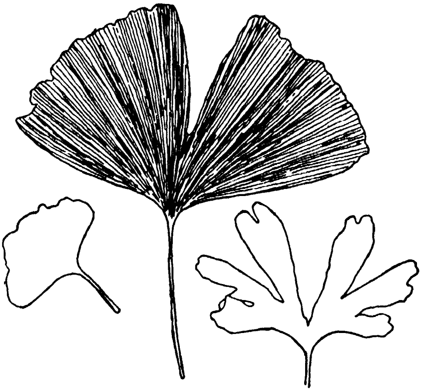

FIG. 274. Leaves of *Ginkgo*. (After Seward.)

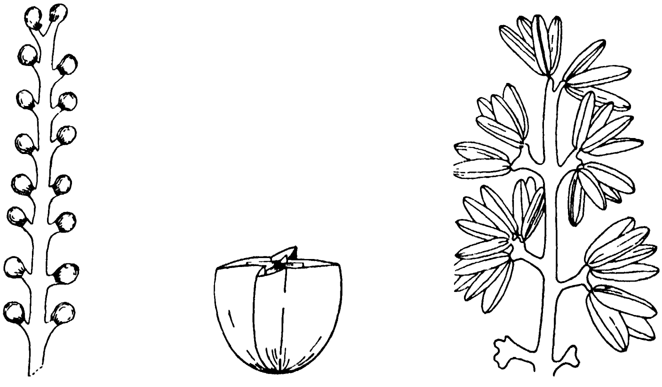

FIG. 275. Caytonialean inflorescences. (After Hamshaw Thomas.)
A. Megasporophyll of *Gristhorpia*.
B. *Antholithus*, male inflorescence.
C. Part of an enlarged pollen sac to show radial arrangement of the four lobes.

The dominant plants throughout Kainozoic times are the broad-leaved flowering plants, the ANGIOSPERMAE. We have already given a sketch of their reproductive processes. There are two sub-classes, the Monocotyledones with one seedling leaf and the Dicotyledones with two seedling leaves. In addition to the fundamental character of the single seedling leaf, the monocotyledons may be distinguished by the following secondary characters : the leaves are usually parallel-veined, the stem is cylindrical, usually without secondary growth, and the parts of the flowers are in threes. The sub-class includes the grasses, palms, lilies, etc. In the dicotyledons the leaves have reticulate veining, in many the stem contains secondary vascular tissues and the parts of the flowers are in fours or fives. Most of our forest trees that are not conifers are dicotyledons, and the sub-class also includes most of the families with conspicuous decorative flowers. Both classes appeared in the Lower Cretaceous, and the dicotyledons are regarded as the more primitive. In the Caytoniales, however, an extinct gymnospermous class of the Jurassic and Rhaetic, represented by the genera *Caytonia* and *Gristhorpia*, we have evidence that the angiospermous habit was nearly attained before the Cretaceous. The seeds were closely packed in small berry-like fruits (Fig. 275A), the almost closed receptacle being possibly evolved from a cupule of pteridosperm type (Fig. 264A and p. 370). The pollen-sacs had three or four loculi radially arranged (Fig. 275B), not bilaterally as in modern flowers, and they grew on a pinnately branched organ. *Sagenopteris* (Fig. 276), frequently found in association with these fruits and believed to be the foliage of the caytonialean plants, ranged back into Upper Triassic. The Caytoniales were probably not ancestral to the modern angiosperms, but may have represented a side-branch of the ancestral stock. There is a considerable body of evidence that this common ancestral stock may have been pteridospermous.

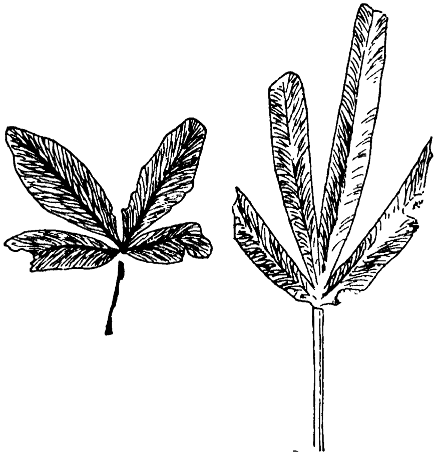
FIG. 276. *Sagenopteris*. (After Seward.)

PART VII

HISTORICAL

CHAPTER LVIII

INTRODUCTION

HISTORICAL Geology is of interest to the pure scientist, and any other intelligent person, because of the information it contains regarding the past history of continents and oceans, of volcanoes and glaciers, and of the development of life. It is important to learn how that information has been deciphered from the rocks. Historical Geology is based upon various tests of relative age, which have already been considered in earlier chapters. They are so fundamental that they are brought together in the following summary.

(1) LAW OF SUPERPOSITION.—Sediments are laid down from above, so that, of two sediments, the upper is the younger, unless the original arrangement has been altered by movement. The movement may be superficial, as for instance in a landslip ; or deep-seated, as in overfolding and thrusting.

(2) A FOSSIL SEQUENCE worked out in one district, where the superposition can be trusted, can be applied elsewhere, even across the seas.

(3) INCLUDED FRAGMENTS often give evidence. Suppose two formations were separated by a fault that prevented our seeing superposition, we might still be able to show that one was later than the other if it contained recognizable pebbles derived from its neighbour.

(4) DIFFERENCES OF FOLDING.—If one formation is much folded throughout a considerable area, and another formation in the same area lies flat, it is probable that the flat formation is not only later than, but unconformable to, the folded formation.

(5) DIFFERENCES OF METAMORPHISM.—If metamorphic and non-metamorphic rocks lie side by side with unfaulted contact, the non-metamorphic rock must be unconformable to the metamorphic.

(6) CURRENT and GRADED BEDDING afford evidence of original order of superposition, and have proved invaluable in folded regions subject to inversion (Fig. 277 ; *cf.* Figs. 4, 6, 7, 279).

The tests just enumerated apply to volcanic rocks as well as to sediments, except that in the case of lavas no help can be got from internal fossils or bedding. Intrusions present special difficulty since they do not conform to the Law of Superposition. Their case may be stated as follows : intrusions are later than rocks which they cut, or bake, and earlier than unconformities, faults or other intrusions, which cut them themselves. They can also be dated with regard to periods of metamorphism.

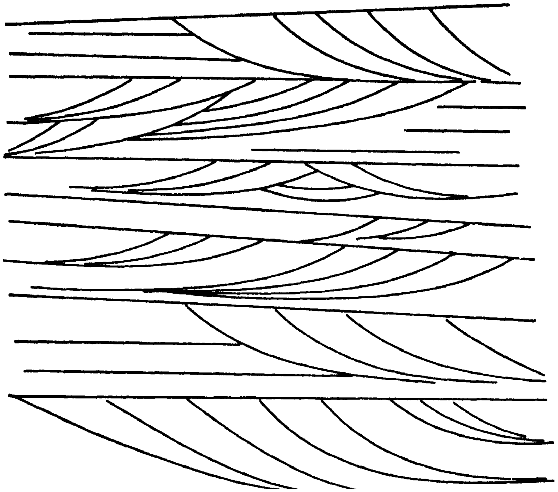

FIG. 277. Current bedding, right way up.

The various divisions of stratigraphical classification are given different names by different authors. The following are fairly widely accepted :

Rocks	*Time*	*Example*
Group of Systems	Era	Palaeozoic
System	Period	Silurian
Series	Epoch	Wenlockian
Stage or Group	Age	Wenlock Limestone
Zone	Hemera	*Cyrtograptus rigidus*

It has already been pointed out that formation is a stratigraphical unit defined by some character chosen for convenience ; also that a formation may be either a big or a small unit (p. 22). In Britain formation often means system, and in America it often means stage. It is convenient to have a term that is not too strictly defined.

History of any sort calls for memory. The following is a list of the major stratigraphical divisions. We shall consider the various systems in turn beginning with the oldest. You are recommended to follow the British outcrops in your spare time upon the Geological Survey map of the British Isles.

System-Group		*System*		*Life*
Kainozoic (Recent Life)		Quaternary	Recent Pleistocene	Age of Man
		Newer Tertiary (Neogene)	Pliocene Miocene	Age of Mammals and the Modern Flora
		Older Tertiary (Palaeogene)	Oligocene Eocene Paleocene	
Mesozoic (Middle Life)		Cretaceous		Age of Reptiles and Ammonites
		Jurassic		
		Triassic	New Red Sandstone	
Palaeozoic (Ancient Life)	Upper	Permian		Age of Amphibia and Coal Flora
		Carboniferous		
		Devonian(Old Red Sandstone)		Age of Fishes
	Lower	Silurian		Age of Trilobites and Brachiopods
		Ordovician		
		Cambrian		
Precambrian				Age of unrecorded life and earlier

CHAPTER LIX

PRECAMBRIAN

THE Precambrian rocks are earlier than any good and useful fossils. Traces of burrows suggestive of worms are about all that one finds.

Most Precambrian rocks are metamorphic, whether of igneous or of sedimentary origin. But there are also, in many districts, non-metamorphic igneous and sedimentary Precambrian rocks.

Certain very extensive outcrops of Precambrian rocks emerge from below a gently tilted Cambrian, or later, cover. The outward inclination of the surrounding rocks recalls vaguely the form of a great shield with its convex surface upwards, and such areas of Precambrian have been called shields. The Canadian Shield and Baltic Shield are the most familiar examples.

The Canadian Shield is interesting geologically for its profusion of pillow lavas. It is also interesting for its immense mineral wealth in particular localities:

At Porcupine gold occurs free in quartz veins associated with a porphyry intrusion. Though the gold is easy to see in exposures near an Indian trail it was not noticed until comparatively lately. Now one of its mines is, or has been, the second producer in the world.

At Cobalt, silver was found quite accidentally when a railway cutting was being made to reach an agricultural district. The silver occurs free in veins associated with a great dolerite sill.

Sudbury is the locality for the world's greatest nickel deposits. The nickel is present as sulphide in association with a variety of gabbro called norite.

In Scotland, Precambrian rocks form the Outer Hebrides and the coastal belt of the North-West Highlands. Their age is fixed by the fact that they are overlain unconformably by fossiliferous Lower Cambrian. They seem to belong to the eastern rim of the Canadian Shield, quite possibly separated from the main exposure by a drifting apart of Europe and America. We shall return to this subject when we consider the Cambrian.

There are two great divisions of the Precambrian in the North-West Highlands that constitute the North-West Foreland of the Caledonian Chain. They are given below, with the younger formation placed at the top, according to a useful convention always adopted in writing a stratigraphical column:

Torridonian
Lewisian

Let us begin with a consideration of the Lewisian. It is a complex consisting almost wholly of metamorphic sedimentary and igneous rocks, the latter predominating. The main outcrops of metamorphic sediments occur at Loch Maree, on the mainland, and in the islands of Coll and Tiree, that lie west of Mull. They are completely crystalline, but their sedimentary origin is revealed in their chemical composition, a matter already discussed under the heading metamorphism (Chapter XXIV). There is, in fact, an

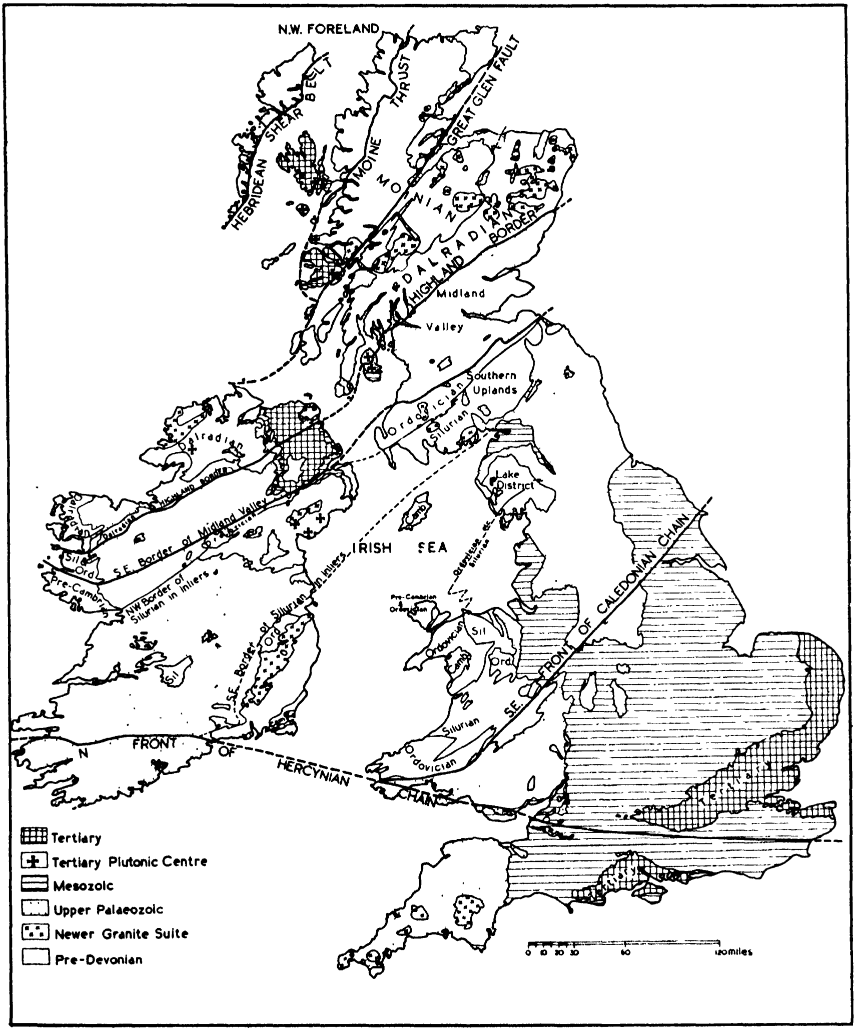

FIG. 278. Geological map of British Isles.

assemblage of rocks with the chemical composition of limestones, carbonaceous and non-carbonaceous shales and sandstones. They are now in the condition of marbles, schists and paragneisses of various kinds.

Most, however, of the Lewisian metamorphic rocks have igneous compositions, showing that they were once granites, quartz-diorites or gabbros. In Coll igneous gneisses intrude sedimentary gneisses. Probably this relation holds in the other districts.

The minerals of the acid igneous gneisses are the same as those that occur in granite ; but hornblende and garnet have been commonly developed in the basic igneous gneisses through interaction of augite, olivine and iron-ore with felspar.

In parts of the Lewisian complex there is a great set of basic north-west dykes of pre-Torridonian age. They may consist of unmetamorphosed dolerite ; but more often they have been affected by shearing movements at a high temperature and converted to hornblende-schist.

In many places bands of shearing are found in the Lewisian rocks, including both the gneisses and the later dykes, of such intensity that the sheared rock has been partly melted by frictionally developed heat. The product from its dull glassy, or flint-like, lustre is known as flinty crush-rock. It would perhaps have been better to call it glassy crush-rock. Till recently it was thought that the exceptional movements that gave rise to this rock were all of pre-Torridonian age, since pebbles of flinty crush-rock occur in Torridonian conglomerates. In 1931, however, flinty crush-rock was found in a fault affecting Torridonian at Stornoway in Lewis. It would seem, therefore, that these movements, while earlier than some parts of the Torridonian, are later than others. The fault at Stornoway forms part of a particularly pronounced shear belt that margins the Outer Hebrides (Fig. 278).

The Torridonian is a great formation of 20,000 feet of unmetamorphosed sediments. It rests with angular unconformity on an irregular eroded surface of the Lewisian, and contains many pebbles derived from the same.

The most characteristic member of the Torridonian is the Middle Torridonian that builds the great Applecross cliffs. It consists of arkose, probably brought by temporary streams from granite masses disintegrating under desert conditions, which would account for the undecomposed condition of the felspars. In keeping with this, dreikanters, or at any rate wind-worn angular stones, are found in the arkose.

The irregularity of the eroded floor, upon which the Torridonian rests, is so great that in places fossil mountains rise 2000 feet up into the heart of the arkose division.

The main mass of the Highlands, east of the Moine Thrust (Figs. 278, 290), consists of metamorphic rocks of somewhat uncertain age. They are cut off from the Cambrian of the North-West Highlands by the great thrust, just mentioned, which effectively prevents us from studying age relations in this direction. Farther south they are unconformably overlain by the Old Red Sandstone, of Devonian age. Near the Highland Border they decrease in metamorphism, and are succeeded by a sparsely fossiliferous Cambro-Ordovician succession. Probably most of the Highland schists are Precambrian rocks, though, on Scandinavian evidence, it seems that many of them received their metamorphism at some stage of the Early Palaeozoic.

Among these Highland schists, not very far in from the Moine Thrust, certain small areas repeat the characters of the Lewisian complex, and are generally correlated with this complex and regarded as older than their more widespread associates. They are called the Lewisian Inliers.

Round about them in the north-west part of the Highlands occur the very extensive Moine, or Moinian, Schists. These are metamorphosed sediments, and the prevalent types are a flaggy quartzo-felspathic gneiss with biotite, which started its career as an impure sandstone, and a micaceous schist or gneiss, that started as a shale.

South-east of the Moinian comes a much more varied set of schists, in which limestones, graphitic schists, boulder beds, quartzites and grits are characteristic members. This varied set, which is of later date than the Moinian, is called the Dalradian, from the old kingdom of Dalriada, partly in the Scottish South-West Highlands, partly in Northern Ireland. The best known boulder bed of the Dalradian is named after Schiehallion and is exposed at intervals from the west coast of Ireland north-eastwards to Aberdeenshire. This particular boulder bed is full of granite erratics and appears to be a consolidated metamorphosed boulder clay of glacial origin.

Three main points of interest may be mentioned in connection with the Highland schists:

(1) In the Moine area in Ross-shire there occurs a great metamorphosed granite called the augen-gneiss of Inchbae. It was intruded into the Moinian before this formation was regionally metamorphosed. It thus produced a hardened contact-altered zone, which has escaped much of the subsequent distortion of the surrounding area during the period of regional metamorphism. Accordingly, near the augen-gneiss, we find hornfelses that retain their minutiae of grain-texture and bedding, including ripple marks, undisturbed. These undistorted hornfelses pass laterally into well foliated schists.

(2) The Ballachulish district of Argyll shows many distinctive formations among its Dalradian schists. This, combined with high relief and good exposures, has allowed the tracing of great recumbent folds. Sometimes for as much as a dozen miles a group of formations lies upside down. During the last few years, study of current bedding has helped us greatly in working out the structure of the district. A first-year student looking at the current bedding of the quartzites at Kinlochleven can nowadays realise that the

rocks are upside down for miles at a time (Fig. 279). These mighty inversions are a manifestation of eddies with horizontal axes, eddies which developed at great depths in the complex flow movements of the solid rocks when these were subjected to mountain-making stresses. Big inversions tend to be accompanied by lags (Chapter XXIII). The Ballachulish Lag is the best-known example in the world.

(3) Among the Dalradian schists it was discovered that the degree of regional metamorphism can be approximately gauged by noting the minerals that have been developed. This subject has already been discussed under the heading metamorphism (Chapter XXIV).

In England and Wales there are only relatively small areas in which Precambrian rocks are exposed. The largest consists of the Anglesey schists. These latter are overlain unconformably by fossiliferous Ordovician, and are said to have furnished pebbles to some late Precambrian and early Cambrian formations of the mainland of North Wales. Very interesting Precambrian exposures also occur in South Wales at St. Davids, and in Shropshire and Leicestershire.

FIG. 279. Inverted current bedding in quartzite, Loch Leven, Inverness-shire.

The Shropshire outcrops include some schists, but are mainly represented by lavas and intrusions of the Wrekin suite (Uriconian) and by immensely thick sediments constituting an upland tract known as the Longmynd (Longmyndian). The Uriconian seems to be earlier than the Longmyndian, since pebbles of Uriconian type are common in Longmyndian conglomerates. The Longmyndian is very strongly tilted, wherever exposed, and is slightly cleaved. For so thick an accumulation, it shows singularly little evidence of current or graded bedding.

Shropshire geology has an irresponsible tendency that makes it a little dangerous to beginners, although perennially fascinating to its own devotees.

There is a risk in constantly meeting unexpected relationships, for all too soon the inquirer may become inured and cease to demand explanations that cannot be furnished.

On the other hand, to such a one as refuses to be satisfied until he understands, the difficulties of Shropshire make a particular appeal. A characteristic Shropshire riddle is presented by the relationships of the Precambrian and the Palaeozoic. The Uriconian commonly emerges from beneath Lower Cambrian. The Longmyndian of the Longmynd close at hand is covered by nothing earlier than Ordovician. This is a remarkable coincidence, when one remembers that the Longmyndian is probably intermediate in date between the Uriconian and the Cambrian, and that it is several thousands of feet thick. A possible solution, which is only advanced to illustrate the reality of the problem, is as follows: The Uriconian, upon which Cambrian has been widely deposited, may belong to a nappe, brought by pre-Cambrian thrusting over the top of the Longmynd sediments. According to this hypothesis the Longmyndian of the nappe was removed by pre-Cambrian erosion, whereas the Longmyndian of the Longmynd remained safely out of sight until denuded of its thrust cover of Uriconian in early Ordovician times.

CHAPTER LX

EARLY PALAEOZOIC (INTRODUCTION)

THE Early, or Lower, Palaeozoic includes three systems beginning, it is thought, some six hundred million years ago :

Silurian
Ordovician
Cambrian

These systems have extensive outcrops in Wales and its borderland, where they were first studied. The name Cambrian comes from the Latin for North Wales ; while Ordovician and Silurian are taken from the Latin for two of the Welsh border tribes.

The Cambrian is the first truly international system, because it is the first to contain fossils that allow of correlation between distant regions. The Cambrian certainly does not mark the dawn of life, but it may mark the adoption of hard parts. If all living forms had remained like sea anemones, devoid of hard parts right up to the present day, there would have been practically no fossils ; and without fossils there would have been no historical Geology worthy of the name.

All three Early Palaeozoic systems are rich in trilobites and brachiopods. These are marine creatures. In the case of brachiopods we have present-day evidence, for the comparatively few brachiopods that survive are all marine. In the case of the trilobites we are dealing with a totally extinct race ; but we are certain that trilobites were marine, because they are again and again found associated with other organisms for which it seems necessary to claim a marine habitat.

The fossils of the Cambrian start with worms, trilobites, hingeless brachiopods and a few forms of doubtful affinities ; but they eventually include all the main invertebrate divisions. Dendroid graptolites probably begin in the Middle Cambrian, while the more typical forms (Graptoloidea) appear in the passage beds between Cambrian and Ordovician ; these latter stop before the end of the Silurian, but the dendroids continue into the Carboniferous. Branched and double forms (diplograptids) are typical of the Ordovician, and *Monograptus* of the Silurian. Ostracoderms appear in the Ordovician, and become numerous before the close of the Silurian.

The Early Palaeozoic rocks of Britain are for the most part involved in the strong folding, which developed the Caledonian Mountain Chain at the close of Silurian times (Fig. 278). This old chain, as already explained, is now largely covered over by later sediments or by the waters of the North Sea. It can be traced north-east from Britain right through Norway. Its north-west margin runs a little in advance of the Moine Thrust through the North-West Highlands, and its south-east margin follows the south-east edge of the Welsh Mountainland.

It has been found that the folded sediments of the great mountain chains of the world very often record long-continued previous subsidence on the site now occupied by the mountains. The name geosyncline has been introduced to denote an elongated region of long-continued and profound subsidence. One of the features, by which a geosyncline is commonly recognised, is the exceptional thickness of its sandy and muddy deposits. Another feature that is attracting attention at the present time is the frequency of graded bedding among geosynclinal sandstones. It is thought that this may be due to disturbances connected with geosynclinal subsidence. If tunamis carry sand and mud well out to sea and drop them through fairly deep water, the coarser material must reach the bottom in advance of the finer. Another feature found in some of the great geosynclines is an association of radiolarian chert and basic pillow lavas, intruded into by serpentine and gabbro. It has been suggested that the radiolarian chert is an abyssal deposit, like the radiolarian ooze of to-day, and that its presence marks the extreme deep-water development of the particular geosyncline. It has further been claimed that geosynclines have been developed by a stretching of the earth's crust, during what may be called a continental drift-apart. The stretching is supposed to thin the crustal layer, and to allow basic and ultrabasic magma to reach the bottom of the sea, there to associate with radiolarian ooze. If such drift-separation continues, a new ocean bed may be developed, covered with products of submarine eruptions. If, as has thrice happened in the post-Cambrian history of Europe, a drift of separation gives place to a drift of approach, then a folded mountain chain comes into being.

Britain has been repeatedly under the sea since Cambrian times, but only during Early Palaeozoic times has much of its surface formed part of a geosyncline. This Early Palaeozoic geosyncline is called the Caledonian Geosyncline. Its characteristic sandstones are greywackes, and often show graded bedding. Radiolarian cherts also occur, in association with pillow lavas and serpentines.

The Caledonian Geosyncline probably started with the same approximate boundaries as those already given for the Caledonian Chain ; but its north-western half seems to have been elevated in fairly early Ordovician times.

The south-east margin of the Caledonian Geosyncline was afforded by a stable platform, intermittently depressed below sea-level. This is marked by a relatively thin accumulation of shallow-water deposits, and is interpreted as the western continuation of the stable Russian Platform, of which we have already spoken.

One further general feature of the Early Palaeozoic history of Britain may be mentioned. There were many volcanoes along the course of the Caledonian Geosyncline during Ordovician times; whereas volcanic action was very restricted during Cambrian and Silurian times.

With this introduction we may consider the three systems one by one.

CHAPTER LXI

CAMBRIAN

THE main British exposures occur in North Wales, Shropshire and in the North-West Highlands. There are small areas elsewhere in Wales and in the English Midlands, and in a narrow strip along the south-east Highland border. In this last it is difficult to distinguish late Cambrian from early Ordovician.

There are great differences between the character, or facies as it is called, of the Cambrian in its various localities. Let us first compare the Welsh and the Shropshire developments.

Welsh facies: very thick, 12,000 feet; continuous; coarse greywacke (often with graded bedding) towards the base, and slate towards the top.

Shropshire facies: thin; discontinuous; quartzite, sandstone and thin limestone, with shale towards the top.

This difference corresponds with

(1) the position of Wales, mostly within the Caledonian Geosyncline, where maximum subsidence occurred during Early Palaeozoic times,

and

(2) the position of Shropshire on the English extension of the Russian Platform, which, though often submerged, subsided relatively slowly and did not give a chance for great thicknesses of sediment to collect.

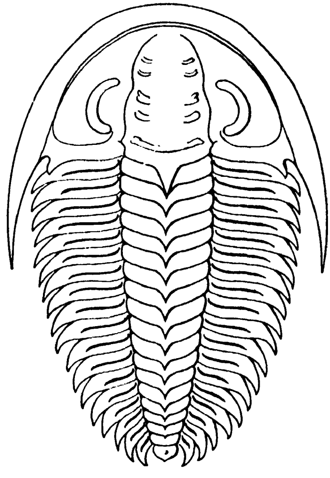

FIG. 280. Lower Cambrian trilobite. (After Geol. Surv.) *Callavia callavii* (Lapworth), × ½.

The Cambrian deposits of Wales and Shropshire differ in their fauna from those of the North-West Highlands. Wales, Shropshire and Scandinavia all belong, according to their Cambrian faunas, to what is known as the European facies. The North-West Highlands belongs to the American facies.

The following columns give the Welsh-English-Scandinavian faunal succession placed in line with the corresponding lithological divisions of North Wales. The fossils named in this list, except ' *Lingula* ', are all genera of trilobites :

Shumardia Series	Tremadoc Slates
Olenus Series	' *Lingula* ' Flags
Paradoxides Series	Menevian Slates ? Upper Harlech Grits
' *Olenellus* ' Series	? Lower Harlech Grits

Olenellus is best put between inverted commas in this connection, for *Olenellus* is an American genus that has not been found in Wales, England or Scandinavia ; it is, however, represented by close relatives (*Callavia*, Fig. 280).

Lingula is put between inverted commas, because the fossil that occurs in the ' *Lingula* ' Flags is now called *Lingulella* (Fig. 282).

The question marks before the two divisions of the Harlech Grits are due to the fact that no fossils have been obtained from them in North Wales, and their correlation with fossiliferous occurrences elsewhere is a bit uncertain.

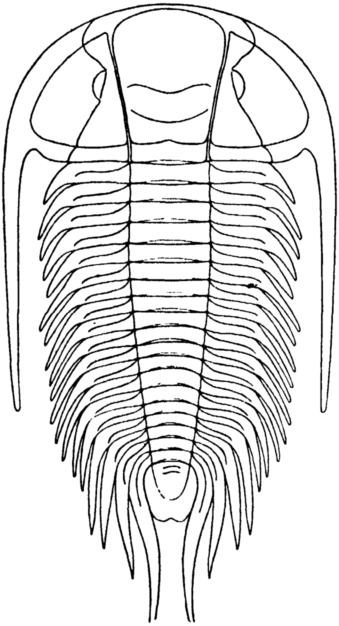

FIG. 281.—Middle Cambrian trilobite. (After Geol. Surv.)
Paradoxides davidis Salter, × ½.

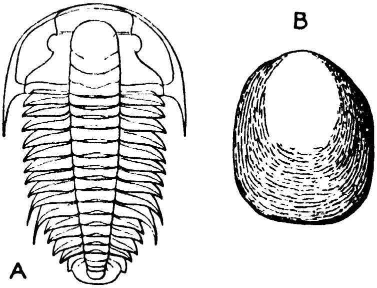

FIG. 282. Trilobite and brachiopod of Olenus Series, Upper Cambrian. (After Geol. Surv.)
A. *Olenus cataractes* Salter, × 1.
B. *Lingulella daviesi* (McCoy), × 1.

The *Shumardia* Series, placed by British geologists at the top of the Cambrian, is regarded by European geologists as forming the bottom of the

Ordovician. This sort of disagreement often occurs in regard to a formation that lies at the top or bottom of a system.

The Cambrian and Ordovician rocks of the North-West Highlands belong to the American facies, as developed, for instance, in parts of Newfoundland. Thus in the North-West Highlands, alone in Europe, we find the American genus *Olenellus*.

The rock succession is :

Durness Limestone - -	1500 feet
Durness Quartzite - -	650 feet

The basal part of the Durness Quartzite rests with angular unconformity on Torridonian and Lewisian, and is unfossiliferous. At a higher level there are innumerable vertical worm-tubes, called pipes. Near the top of the quartzite are some shales that have yielded *Olenellus*.

The Durness Limestone is largely unfossiliferous, but its upper part contains a gastropod and cephalopod fauna of American Lower Ordovician type. It is generally admitted that this fossiliferous upper part of the Durness Limestone is of Lower Ordovician date. Perhaps the Middle and Upper Cambrian are missing owing to disconformity. Perhaps they are represented within the almost unfossiliferous lower part of the limestone.

Let us return to the resemblances which exist between the Cambrian, and probable Lower Ordovician, of the Scottish North-West Highlands and the contemporaneous rocks of parts of Newfoundland and the Appalachian Mountains. We find :

(1) The faunas are the same.

(2) The rock types, quartzite and limestone, are the same though they do not agree in their detailed arrangement.

(3) The structural position is the same. Both lie at the north-west edge of the Caledonian Mountain Chain, folded and thrust in Early or Mid-Palaeozoic times.

These resemblances certainly support the view that America and Europe have drifted apart ; but they certainly do not prove any such proposition.

Fauna.—A few words may be added in regard to the Cambrian fauna. Fully 1000 species have been described from the Cambrian, two-thirds of which are trilobites and brachiopods. The life was entirely invertebrate. In the Lower Cambrian, in the bottom part, we only find remains of worms and trilobites, but soon brachiopods appear (most of them hingeless as *Lingulella*, Fig. 282), uncoiled gastropods and pteropods (as *Hyolithes*, *cf.* Fig. 175E). No lamellibranchs or cephalopods are known before the close of the Lower Cambrian. What appear to be primitive corals start in the Middle Cambrian. Graptolites scarcely enter British stratigraphy before the *Shumardia* Series (*Dictyonema* and *Clonograptus*, Fig. 283).

The stratigraphical value of fossils is well illustrated in the development of knowledge regarding the American Cambrian. It happened that the first American Cambrian fossils, of earlier date than the *Olenus* Series, were found in rocks which had been thrust upon the top of Ordovician rocks. The thrusts were overlooked, and it was thought that, according to the Law of Superposition, these fossils were younger than the underlying Ordovician. Barrande, however, saw casts of the fossils sent to European museums, and recognising them as of Cambrian types said they must be of pre-Ordovician age. After many years the Americans found that this was the case.

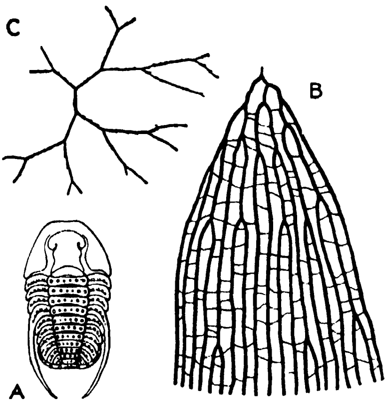

FIG. 283. Trilobite and graptolites of Shumardia Series, Upper Cambrian. (After Geol. Surv.)

A, *Shumardia pusilla* (Sars), × 5; B. *Dictyonema flabelliforme* (Eichwald), × 1; C, *Clonograptus tenellus* (Linnarson), × 1.

Even when the Americans did recognise that their *Olenellus* and *Paradoxides* beds were of Cambrian date, they were still misled by thrusts, and regarded *Olenellus* as younger than *Paradoxides*. Again a European, this time Brögger, put them right. He based upon the fact that the European relatives of *Olenellus* are older than *Paradoxides*.

STRUCTURE.—It is best to consider the structure of the Caledonian Chain as a whole, at the close of the Silurian (Chapter LXIV). For the moment we need only recall that the Cambrian of the Welsh Mountainland has been involved in the great compressions that produced this Caledonian Chain. One result has proved of great economic importance.

ECONOMICS.—In Wales the greatest slate quarries of the world, Penrhyn and Llanberis, are in Cambrian slates, which owe their cleavage to Caledonian mountain stress.

In the same country manganese ore has been worked in beds, and gold in veins.

In England, south-east of the Caledonian Chain, quartzite has been largely quarried as road metal.

In Scotland, north-west of the same, the Durness Quartzite and Limestone would be of value if they occurred in populous districts.

CHAPTER LXII

ORDOVICIAN

THE second system of the Early Palaeozoic has been divided into four series :

Ashgillian } Bala
Caradocian }
Llandeilian
Arenigian

All but one of these names are based upon Welsh localities. Ashgill is in the English Lake District.

The main British exposures from south-east to north-west are in :

(1) Shropshire.
(2) Welsh Mountainland.
(3) English Lake District.
(4) The north-west portion of the Scottish Southern Uplands.
(5) The south-east and north-west margins of the Highlands. Here, in the Highland Border Series, on the one side, and the Durness Limestone on the other, there is difficulty in deciding what should be called Upper Cambrian and what Lower Ordovician. The Highland Border Series includes some pillow lavas, cherts and black shales, very like the Ballantrae rocks of the Southern Uplands, to be described presently.

Let us consider a problem presented by the stratigraphy of the Ordovician and Silurian rocks of the Southern Uplands. These rocks have been greatly folded in the formation of the Caledonian Chain (Fig. 278). They stand as a rule nearly vertical, often with reversed dips. This, combined with discontinuous exposure, rendered it impossible to establish age relations by means of the Law of Superposition. Moreover there is no clearly marked succession of rock types. In such circumstances the most hopeful approach to the succession problem is by way of fossils. At first very confusing results were obtained. The most commonly found fossils are graptolites, and it seemed, to begin with, that the graptolites occurred in perfectly haphazard fashion. However, Lapworth, a young English schoolmaster, who had come to Galashiels just to live in the Scott country, at last settled the problem that previously had baffled all experts. By keeping his collections of graptolites from each outcrop separate he found that the graptolite faunas do occur in a definite order. Where in a section there is an apparent repetition of graptolite faunas, it can always be accounted for by a repetition of horizons through folding or faulting. Thus in 1878 Lapworth not only settled the succession of the Southern Uplands, but also gave geologists of all lands a new weapon for attacking the Ordovician and Silurian; namely a definite time-sequence of graptolite faunas.

Now for another problem. Both in the Ordovician and Silurian there are two main lithological facies:

1. Graptolitic black shales with associated greywackes and grey shales.
2. Shelly sandstones and limestones.

These different lithological facies have very different fossils, even where they are contemporaneous and occupy neighbouring regions. The graptolitic black shales contain little else but graptolites and hingeless brachiopods, many of which may have lived attached to floating seaweed (Fig. 287). The shelly sandstones contain trilobites and hinged brachiopods (Fig. 286), with few or no graptolites or hingeless brachiopods. Thus in the Southern Uplands Lapworth had not only to arrange the graptolite faunas in order, but also to establish correlations between each graptolitic fauna and its contemporaneous shelly fauna. This he did by studying interstratifications. Where he found some particular shelly fauna interstratified between beds that yielded some particular graptolitic fauna, or vice versa, he deduced that the interstratified shelly and graptolitic faunas must have been contemporaneous within the limits of geological observation. It was hard work to get all the evidence pieced together, but eventually he won through.

Lapworth studied in particular the Moffat Shales, partly belonging to the Ordovician, and partly to the Silurian. These at Moffat are black graptolitic shales, only 200 feet thick. At Girvan, their time-equivalents are on the whole non-graptolitic, but they contain enough graptolitic beds to allow of age comparisons with the Moffat district. Instead of being black shales, the equivalent Girvan formations are for the most part sandy and conglomeratic, with occasional limestones; and instead of being only 200 feet thick they are some 5,000 feet. The change of facies can be studied in the

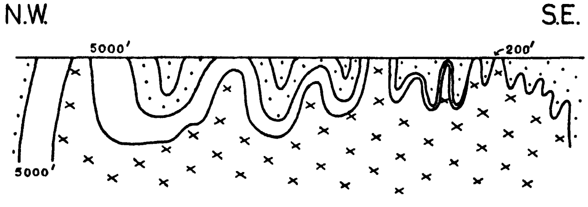

FIG. 284. Diagrammatic presentation of the Girvan-Moffat shales and their equivalents, unornamented; older rocks, crossed; younger rocks, dotted.

intervening district, for there are many folds that take the horizons again and again through the present-day surface determined by erosion (Fig. 284).

We shall return to this contrast between Moffat and Girvan after dealing with the basal relations and vulcanicity of the Ordovician throughout Britain.

BASAL RELATIONS.—It is now generally accepted that throughout Wales the Ordovician follows unconformably on the Cambrian; and that the Tremadoc slates are absent except in the immediate neighbourhood of the Harlech dome. It is on this account that British geologists group the Tremadoc as Upper Cambrian, instead of following Scandinavian geologists and placing it with the Ordovician. It is uncertain whether the erosion that separates Cambrian and Ordovician in Wales means an actual uplift above sea-level. It may have been the result of shallow sea conditions.

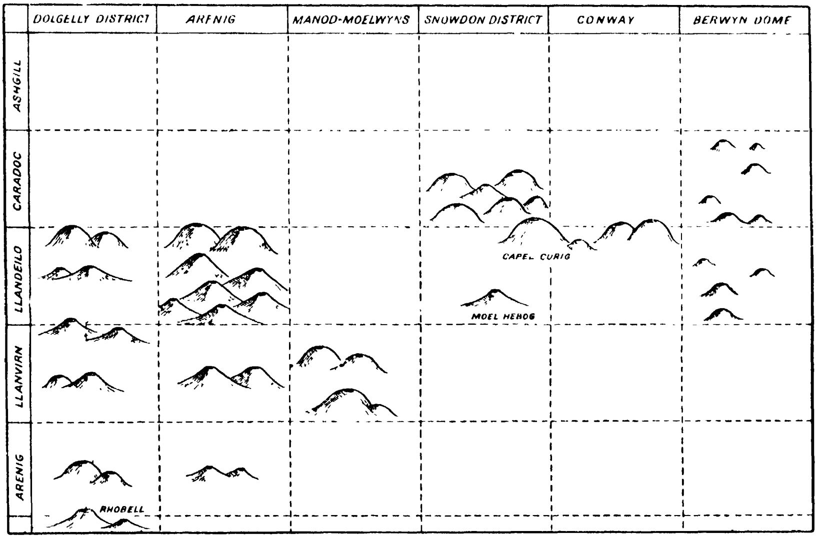

FIG. 285. Vulcanicity during Ordovician times. (After B. Smith and T. N. George, Geol. Surv.)
On this diagram Upper Arenigian is called Llanvirn.

In Anglesey the Ordovician rests on Precambrian schists. In the Lake District and Southern Uplands, so far as we know, the base of the Ordovician is nowhere seen.

VOLCANOES.—At one place or another Wales was volcanic through most of Ordovician times (Fig. 285). Notable examples are afforded by the Arenig volcanoes of Arenigian and Llandeilian times, and the Snowdon volcanoes of Caradocian times (formerly considered Llandeilian). Many of these Welsh volcanoes emitted rhyolite, either as ash or lava. The Lake District had great volcanoes in Llandeilian times, mainly andesitic with a large proportion of ash. In the Southern Uplands the chief activity was during the Arenigian, when there were widespread submarine flows of pillow lavas, which were basic, as all pillow lavas are. These Arenigian pillow lavas are particularly well exposed on the Ayrshire coast near Ballantrae.

SEDIMENTARY SUCCESSION.—The sedimentary succession will be considered under two local heads.

1. SOUTHERN UPLANDS.—The Arenigian pillow lavas of Ballantrae, intruded into by serpentines and gabbros, form the basal part of the Ordovician throughout the Southern Uplands, and probably extended far to the north-west. They were followed by clear-water, perhaps abyssal, radiolarian cherts that continue from Upper Arenigian to Lower Llandeilian times (authors differ in their definition of Llandeilian, and there is a tendency at the present time to confine the term to what is here called Lower Llandeilian).

At the close of Lower Llandeilian times, elevation occurred to the north-west, in the region to-day occupied by the Highlands and the Midland Valley. This elevation affected the Girvan district, but not Moffat, farther south-east. (Girvan lies on the north-west margin of the predominantly Ordovician outcrop of the Southern Uplands as drawn in Fig. 278, while Moffat lies within the predominantly Silurian outcrop.) It greatly restricted the Caledonian Geosyncline. From Upper Llandeilian times onward, the Girvan district remained near the north-west coast of the geosyncline ; but was generally under water as a result of intermittent submergence, deep enough, when it occurred, to allow of the retention of great thicknesses of sediments, separated by local unconformities. These sediments include a large proportion of conglomerates, many shelly horizons and a rather extensive limestone, the Stinchar Limestone of Upper Llandeilian age. A much more local limestone, the Craighead, is of slightly later date than the Stinchar.

Meanwhile the Moffat district remained continuously submerged near the deep-water axis of the Caledonian Geosyncline. Out of reach of the pebbles and sands of the Girvan shallows, it only received thin graptolitic muds. The Ordovician part of the Moffat Shales is divided according to its fossils into :

Hartfell Shales = Caradocian and Ashgillian
Glenkiln Shales = Upper Llandeilian.

2. ENGLAND AND WALES.—The English Lake District and Wales show a much thicker development than at Moffat. Their rocks contain a great deal of sandy material, with some shell beds and occasional limestones. Thus we find the Coniston and Keisley Limestones of the Lake District and Pennines and the Llandeilo, Bala and Rhiwlas Limestones of Wales. With the exception of the Llandeilo, all these limestones are of Caradocian or Ashgillian date. Evidently, after passing the deep-water axis in the Moffat district, we arrive in the Lake District and Wales at comparatively shallow water conditions on the south-east side of the geosyncline. In the platform

region, except at the very margin of the geosyncline, near Caer Caradoc, Ordovician is absent. This statement does not apply to Cornwall, where fossiliferous Ordovician has been found of a type corresponding with occurrences in Brittany and Normandy.

FAUNA.—We have sufficiently contrasted the graptolitic faunas that accumulated on the quiet, and often deep, bottoms of the Caledonian Geosyncline with the shelly faunas of the agitated shallow margins. During Ordovician times another sort of contrast distinguished the shelly faunas (trilobites and hinged brachiopods) on the Girvan and Welsh sides respectively of the geosyncline. Contemporaneous species, and even genera, in the two localities are very often quite distinct. It appears that the shallow water organisms could not cross the Moffat deep. The Girvan shells are often closely allied to contemporaneous American forms, but not to so marked an extent as in the case of the Durness Limestone of rather earlier date. The contrast between the Girvan and Welsh shelly faunas diminishes in the later stages of the Ordovician, and disappears with the Silurian, as though by that time the deep water of the geosynclinal axis had locally become silted up.

The following gives a brief review of some of the main features of the Ordovician faunas.

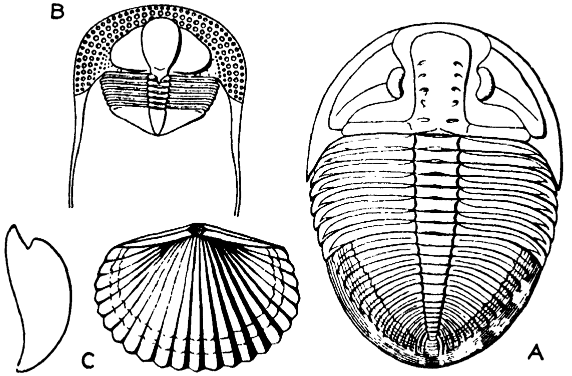

FIG. 286. Ordovician shell fauna : trilobites and brachiopod. (After Geol. Surv.)

A. *Ogygiocaris* [*Ogygia*] *buchi* (Brongniart) × ½.
B. *Cryptolithus* [*Trinucleus*] cf. *concentricus* (Eaton), × 1.
C. *Orthis* (*Dinorthis*) *flabellulum* J. de C. Sowerby, × 1.

Trilobites and brachiopods are still very important, as in the Cambrian (Fig. 286). The trilobites include *Ogygiocaris*, *Cryptolithus* [*Trinucleus*] and *Calymene*, which last continues from Ordovician to Silurian.

The hinged brachiopods, belonging to the shelly fauna, are represented by *Orthis*, which, *sensu lato*, continues to the Carboniferous.

The hingeless brachiopods, which go with the graptolitic facies, include *Lingula* and *Orbiculoidea*, both very long-lived forms; *Lingula* is alive to-day (Fig. 171A).

The great difference from the Cambrian is the development of graptolites (Fig. 287), though some early forms, as *Dictyonema*, started in Britain in the Tremadoc Slates (Fig. 283). In the Lower Ordovician the main genera are *Tetragraptus* and *Didymograptus*. Then follow *Nemagraptus*, *Diplograptus* (Fig. 133C), *Climacograptus* and *Dicranograptus*,

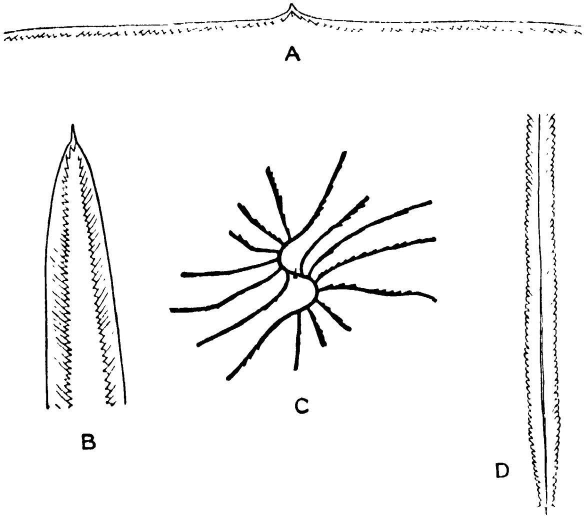

FIG. 287. Ordovician graptolites. (After Geol. Surv.)

A. *Didymograptus extensus* (Hall), × 1; B. *Didymograptus murchisoni* (Beck), × 1; C. *Nemagraptus gracilis* (Hall), × 1; D. *Diplograptus* [*Mesograptus*] *multidens* Elles and Wood, × 1.

Corals, bryozoa and coiled gastropods are important in some limestones; and the corals show compound tendencies.

Scales of ostracoderms have been detected in America.

STRUCTURE.—The Ordovician of the Southern Uplands, English Lake District and Welsh Mountainland are all included within the Caledonian Chain, and are intensely folded. Their shales have in many localities been cleaved into slates.

ECONOMICS.—Slates—cleaved ashes in the Lake District and cleaved shales in Wales—are much worked.

Intrusions are quarried for paving sets and road metal in Wales.

CHAPTER LXIII

SILURIAN

THE third and last system of the Early Palaeozoic has been divided into four series :

Downtonian
Ludlovian
Wenlockian
Llandoverian

The names are all taken from localities along the English-Welsh border.

The main outcrops occur near those of the Ordovician in the Southern Uplands, Lake District, Wales and Shropshire (Fig. 278).

In many exposures, at Girvan and in Wales, but not in the intervening districts of Moffat and the Lakes, the Silurian is unconformable to the Ordovician. Almost everywhere vulcanicity died down, though represented in the Bristol area in Llandoverian times and reviving in Kincardineshire towards the close of the period.

The sedimentary history of the Silurian is best summarized with reference to the Caledonian Geosyncline, to which we have referred so often. The north-west margin of the geosyncline occupied the same position as during the greater part of Ordovician times, that is some little distance north-west of Girvan. The south-east margin continued where it had been in Cambrian times, namely against the Shropshire continuation of the Russian Platform, in other words along the south-east edge of the Welsh Mountainland. The north-eastwardly directed deep-water axis started at Moffat at the beginning of Silurian times, but soon began to migrate south-eastwards, at right angles to its strike, into England and Wales. Thus in Lower Llandoverian times, Moffat still lay within the central black graptolitic shale-belt of the geosyncline ; and the top division of the Moffat Shales, called the Birkhill Shales, belongs to this date. Later, during Upper Llandoverian (otherwise known as Tarranonian) times, grits, often with graded bedding, invaded the Moffat district from the north ; and to find the corresponding black shale development one has to travel to the English Lake District. In still later stages, the deep-water, or black-shale, axis, now but vaguely marked, migrated to North Wales. Eventually in Downtonian times the geosyncline as a whole faded away ; the sea became landlocked, shallow and often fresh.

During Llandoverian to Ludlovian times the sediments north-west and south-east of the black-shale axis were relatively sandy and thick, often graded-bedded, but also including shelly horizons. The thick south-eastern development in Wales thins out again when followed farther south-east, beyond the limits of the Welsh Mountainland. Here on the Shropshire extension of the stable Russian Platform the sediments are noteworthy, not only for their relative thinness, but also for the presence of prominent shelly limestones, in both the Wenlockian and Ludlovian. The Wenlock Limestone is famous for the beauty of its fossils. Incidentally, it is of the same date as the limestone over which Niagara falls, on the other side of the Atlantic.

At many stages in the development and filling of the Caledonian Geosyncline, conspicuous examples of slip bedding have been produced and preserved. Production and preservation are in this case quite independent phenomena, but both would be favoured on geosynclinal submarine slopes shaken by intermittent earthquakes. It would, of course, be dangerous to over-emphasize this aspect of the matter, since slip bedding, on a small scale, is a commonplace in certain non-geosynclinal sediments, such as the Middle Torridonian arkoses and various Carboniferous sandstones. At the same time, the most impressive instances of slip bedding as yet described from Britain occur in the geosynclinal Ludlovian of Denbighshire in North Wales. Here submarine landslips, exceeding a thousand feet in individual thickness and traceable for several miles across country, are floored and covered by relatively undisturbed strata. The Denbighshire area lies on the fringe of the Welsh region of post-Ludlovian Caledonian cleavage. In it cleavage is only locally developed, and with a crude incipient character that has won for it the title 'fracture-cleavage'. This fracture-cleavage exhibits much greater concentration and irregularity in the landslipped material than in the intervening unslipped sediments. It therefore appears that the slipped material acquired a special susceptibility to subsequent cleavage as a result of the churning which it suffered in the process of slipping. This interpretation is comparatively recent, since there has been an understandable tendency in the past to refer the contortion and cleavage of the Denbighshire rocks to one and the same date, namely post-Ludlovian; but, as O. T. Jones has pointed out, this is impossible since the contorted Ludlovian slips are overlain with unbroken stratigraphical contact by uncontorted Ludlovian.

The Downtonian is only preserved in the Midland Valley of Scotland and at the border of the Welsh Mountainland and is a passage series, variously placed by stratigraphers with the Silurian or Devonian. In Britain it furnishes a lithological transition between the marine facies of the Silurian and the continental facies, known as Old Red Sandstone, of the Devonian. Some beds contain *Lingula* and marine gastropods, *Platyschisma* (Fig. 288);

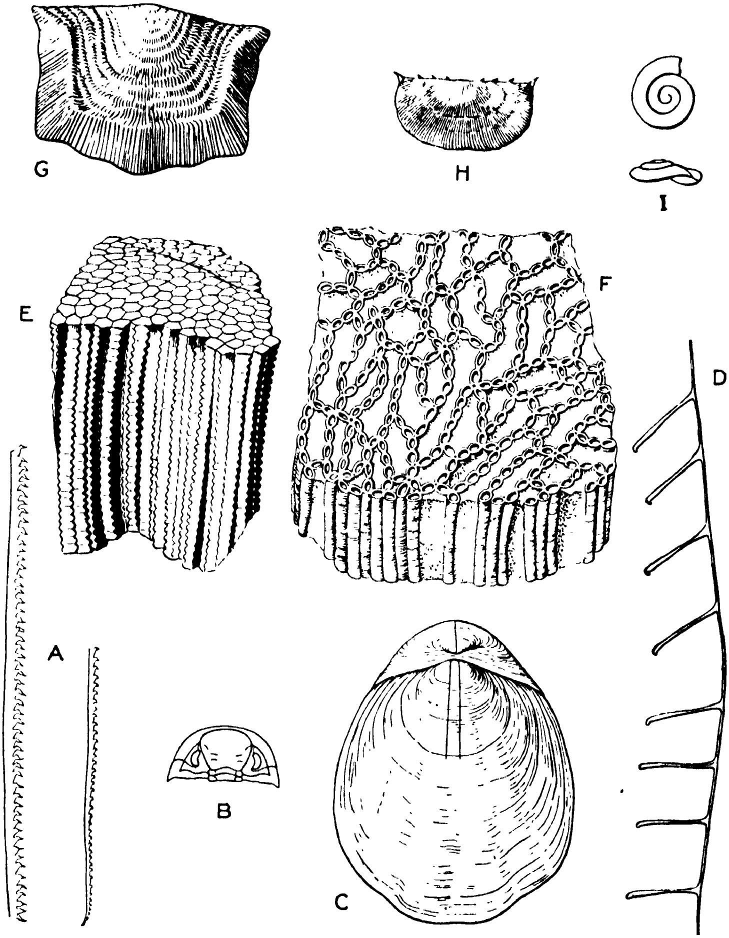

FIG. 288. Silurian graptolites, trilobite, brachiopods, corals and gastropod. (After Geol. Surv.)

Downtonian : I. *Platyschisma helicites* (J. de Sowerby), × 1.
Ludlovian : H. *Chonetes striatellus* (Dalman), × 1.
Wenlockian : E. *Favosites gotlandicus* Lamarck, × 1 ; F. *Halysites catenulata* (Martini), × 1 ; G. *Leptaena rhomboidalis* (Wilckens), × 1.
Llandoverian : A. *Monograptus sedgwicki* (Portlock), × 1 ; B. *Portlockia* [*Phacops*] *elliptifrons* (Esmark), × 1 ; C. *Pentamerus oblongus* Lamarck, × ¾ ; D. *Rastrites maximus* Carruthers, × 1.

others ostracoderms (*cf.* Fig. 200–202) and eurypterids (*cf.* Fig. 161). Bone-beds occur, marking perhaps disasters, such as an incursion of the sea into fresh water.

Fauna.—In the first place let us recall that from the beginning of Silurian times there ceased to be any marked contrast between the faunas contemporaneously living along the two margins of the Caledonian Geosyncline.

The shelly faunas of the thoroughly marine portion of the Silurian, like their Ordovician predecessors, were rich in hinged brachiopods and trilobites. Among the former, *Orthis* remained abundant, while *Leptaena* and the robust *Pentamerus* appeared, or at any rate became abundant (Fig. 288). Among the trilobites *Dalmanites* and *Calymene* may be mentioned. In the limestones of the period tabulate corals, such as *Halysites* and *Favosites*, are accompanied by rugose forms, along with crinoids and bryozoa. Chambered cephalopods are typically straight, like *Orthoceras*, a genus already prominent in the Ordovician (*cf*. Fig. 182A).

The graptolitic associations of the Silurian continued to include hingeless brachiopods, such as *Lingula*. The most typical Silurian graptolites are *Monograptus* and *Rastrites* (Figs. 135, 288). All graptolites, except the dendroids, such as *Dictyonema* (*cf*. Fig. 283), became extinct before the close of the Ludlovian.

In Scotland the Wenlockian and Ludlovian have yielded eurypterids (*cf*. Figs. 161, 162) and an early scorpion (Fig. 160).

Simple fish and land plants are first met with, so far as Britain is concerned, in the Ludlovian (*cf*. from Australia, Fig. 251).

The eurypterids and ostracoderms of the Downtonian have already been mentioned.

Structure.—The British Silurian is very strongly folded in almost all its exposures (see Chapter LXIV); but it has escaped at Lesmahagow, Lanarkshire, on the north-west side of the Caledonian Geosyncline (as restricted since Upper Llandeilian times), and also beyond the east border of the Welsh Mountainland on the south-east side of the same depression. The folded Silurian is often cleaved in the Lake District and Wales, and at the Highland Border in the extreme west of Ireland.

Economics.—Silurian slates are quarried in North Wales and the Lake District; but are less important than those of Ordovician and Cambrian date. They are the youngest slates worked in Britain, except for some in the extreme south, which belong to the Hercynian Chain, to be discussed presently.

Limestones bordering the Welsh Mountainland have been extensively quarried.

CHAPTER LXIV

CALEDONIAN MOUNTAINS

THE development of the Caledonian Chain was one of the most momentous events in the geological history of Europe. The relics of its ancient mountains extend south-west throughout the whole length of Norway. They are there practically naked, but are abruptly truncated at the north-west coast line. In Great Britain they are more than half hidden beneath later deposits, but still they enable us to piece together fairly complete cross-sections of the chain, from the Moine Thrust on the north-west to the border of the Welsh Mountainland on the south-east (Fig. 278).

The Midland Valley of Scotland, with its south-westward continuation across Ireland, divides the Caledonian Mountain exposures into two unequal parts. To the north-west lie the Scottish and Donegal Highlands, mainly composed of crystalline schists, Moinian and Dalradian. To the south-east lie the Southern Uplands of Scotland, reappearing in County Down, the English Lake District, and the Welsh and Wicklow Mountainlands. Here the folded rocks are often intensely cleaved, but have seldom developed conspicuous metamorphic minerals, except for some garnet in the Isle of Man and the Lake District.

The metamorphism of the Highlands seems in the main to be pre-Silurian. Comparison with Norway, taken in conjunction with the local evidence, suggests that it is to a large extent of intra-Ordovician date. Very striking intra-Ordovician unconformities have been demonstrated: near Girvan, where the Midland Valley and Southern Uplands meet on the West Coast of Scotland; at Pomeroy, on the Highland Border west of the Antrim Tertiaries; and in the exposed Palaeozoic floor of the Midland Valley, on the Atlantic coast of Ireland. These unconformities may be interpreted as accompaniments of the chief upheaval of the Highlands. There can, however, be no doubt that compressive upheaval was renewed at the close of the Silurian in the Highlands, and to a minor extent during Lower and Middle Devonian times; and that, south-east of the Midland Valley, the post-Silurian disturbances were dominant.

American geologists tend to distinguish intra-, or immediately post-, Ordovician movements under the title Taconic, and to separate them from late or post-Silurian movements to which they restrict the name Caledonian. This is merely a matter of choice, for it is not imagined that any particular episode of mountain-making has been limited to an instant of time. In the present account, Taconic movements are treated as a prominent constituent of the Caledonian, the latter being interpreted in a broad inclusive sense.

As might be expected there is often great difficulty in separating the effects of the various movements that have built up the great Caledonian Chain. In the following generalizations this difficulty is allowed to lie dormant.

In the Scottish Highlands a north-east axis can be drawn, roughly midway between the Great Glen Fault and Highland Border of Fig. 278, from which overthrust movement has occurred outwards in both directions: north-westwards and south-eastwards. This overthrust movement is most clearly seen in north-westward travel upon the Moine Thrust, as exposed in the North-West Highlands, where the minimum movement disclosed is 10 miles, and in oppositely directed south-eastward travel of the Norwegian mountains over the Swedish foreland in Jemtland, where the minimum movement disclosed is actually 90 miles. It is also revealed by careful study of eddies in the Dalradian Schists (Chapter LIX): the Fort William and Ballachulish Eddies, which lie geographically between the Great Glen Fault and the median axis, have revolved with their upper portions travelling north-west in relation to their lower portions; the Southern Highland Eddy, on the other side of the axis, has had a reverse spin (Fig. 289).

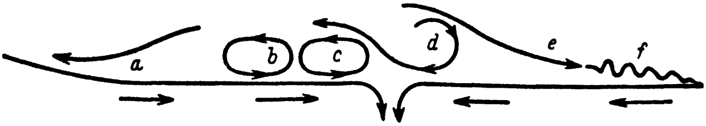

Fig. 289. Diagram suggestive of types of movement illustrated in the Caledonian Chain.

a: N.W. overthrusting N.W. Highlands. *b* and *c*: Eddies and lags combined with N.W. over-shear, Fort William and Ballachulish. *d*: Eddy and lag combined with S.E. over-shear, S.E. Highlands. *e*: S.E. overthrusting, Scandinavia. *f*: Buckling, Southern Uplands, Wales and Oslo district. *e* and *f* are to a large extent local alternatives.

(After Bailey and Holtedahl, 1937.)

The Highland Border is a particularly complex structural zone, where the Highland rocks plunge steeply, with some overturning, beneath the present level of erosion. The history of this border has been obscured by Devonian and later deposition and movement (see Chapter LXV).

The folding of the Southern Uplands, the Lake District and the Welsh Mountainland seldom reproduces the complexities of the Highlands, though very considerable south-eastward thrusting of Caledonian age is manifested in Anglesey. The folding is most developed in the Southern Uplands, where a great number of steep tightly compressed anticlines and synclines have been detected. The more north-westerly have a tendency to overturn towards the north-west, and the more south-easterly towards the south-east. (This feature is not indicated in the diagram, Fig. 284.) It looks as though the great south-eastward overthrusting of Jemtland is for the most part replaced in Britain by close folding, without frontal fracture. Quite probably the folding has been associated in places with basal separation from a relatively resistant floor, which in the Southern Uplands appears to have been furnished by Arenigian lavas and intrusions. Such separation, allowing of independent folding of cover and basement, is called in French *décollement*, meaning ungluing.

It is a rather curious fact, which still awaits explanation, that there is much more Caledonian cleavage developed in Wales and the Lake District than in the Southern Uplands.

Up to this stage we have spoken of overthrust movement directed outwards from an axis in the Highlands. Movement is always relative. The direction of overthrust movement means in Tectonics the direction of movement at overlying levels relative to that at underlying levels. The great thrust-masses of the North-West Highlands have moved north-westwards relative to their foundations. Equally truly these foundations have moved south-eastwards relatively to the supernatant thrust-masses. We are therefore quite justified, if we find it convenient, to speak of the direction of underthrust, instead of overthrust. This practice is, as a matter of fact, helpful in attempting to visualize the growth of the Caledonian Chain. Adopting the underthrust phraseology, we may say that the structure of the Caledonian Chain reveals an approach, from north-west and south-east, of the foundation rocks upon which the sediments of the chain had accumulated. Where the two subterranean currents of foundation rocks met, they flowed down into the depths, in complex forms, which erosion has not yet exposed to view. Meanwhile the sedimentary cover accommodated itself to its diminishing base with thrusts and folds, that passed in deeply covered portions into eddies with horizontal axes.

While every exposure of the Caledonian Chain has its own fascination, there is no doubt the North-West Highlands makes the most general appeal. This is partly due to the magnitude of the Moine and associated thrusts, the striking contrast of the stratigraphical divisions, and the perfection of the exposures. It is also partly due to the advertisement which the district got from the fact that leading British geologists for many years did not recognise the existence of the thrusts, and, applying the Law of Superposition, wrongly concluded that the Moine Schist is of later date than the Durness Limestone, which underlies it.

In brief, the undisturbed succession in the North-West Highlands is :

Durness Limestone—Cambrian and Ordovician
Durness Quartzite —Lower Cambrian

unconformity
Torridonian —Precambrian

unconformity
Lewisian —Precambrian

In addition there are syenite masses and many sills cutting the Durness Limestone and older rocks ; and, finally, the Moine Schist, probably Precambrian, though likely metamorphosed during Early Palaeozoic times.

Thrusting of post-Cambrian date has often carried both Torridonian and Lewisian in great slices for miles over the top of the Cambrian or Ordovician (Fig. 290). When we see Lewisian gneiss overlying Durness Limestone, there can nowadays be no doubt that the gneiss has been thrust into this unorthodox position. We recognise the overthrust gneiss as Lewisian by : (1) its characters, and (2) the fact that it is often unconformably overlain by Torridonian and Cambrian. We also note along the basal contact intense shearing leading to mylonite.

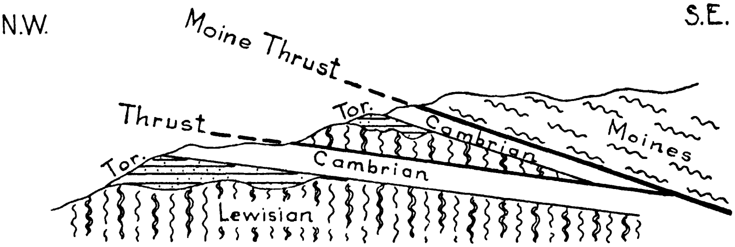

FIG. 290. Diagrammatic section through the North-West Highlands showing two unconformities and two thrusts.

There are many thrusts in the North-West Highlands, and above the top one, the Moine Thrust itself, lies the great Moine Schist. While we are uncertain of the exact age of the Moine Schist, we know at any rate that it could not have been deposited as sediment on top of the local Cambrian and Ordovician, because it is crystallized by a metamorphism that has not affected the underlying formations. In keeping with this, it is found that the Moine Thrust cuts across underlying formations and structures, and is lined with mylonite.

Among the many structural interests of the North-West Highlands is a klippe of the Moine Nappe isolated by erosion at Durness, 10 miles in advance of the main outcrop of the Moine Thrust across Loch Erriboll. This shows that the Moine Thrust must have brought forward the Moine Schist for fully

10 miles over the top of the Cambrian. The Durness klippe owes its preservation to pre-erosional down-faulting (Fig. 291).

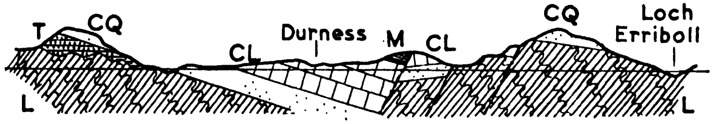

FIG. 291. Section across klippe of Moine Schist at Durness.
L, Lewisian ; T, Torridonian ; CQ, Cambrian Quartzite ; CL, Cambro-Ordovician Limestone ; M, Moine Schist on Moine Thrust.

Below a thrust one often finds a broken zone resting upon what is known as a sole, and consisting of piled up thrust slices, all dipping towards the direction from which the overlying nappe has come. These slices are arranged something like the scales of a fish. The structure is therefore called schuppen structure, from a German word meaning scales (Fig. 292).

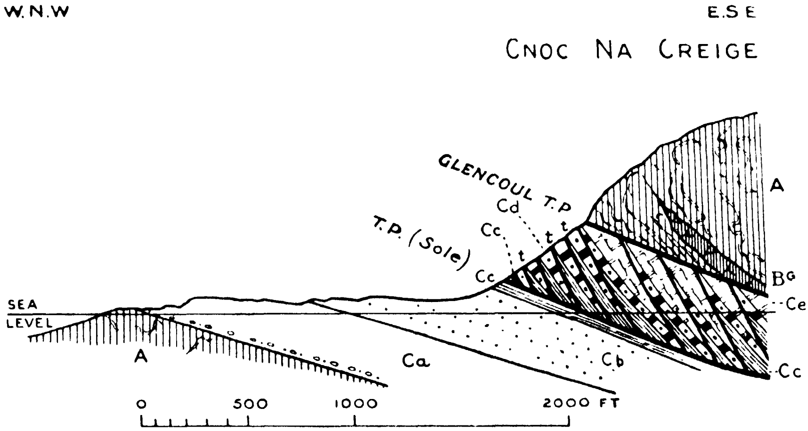

FIG. 292. Section at Loch Glencoul, N.W. Highlands, illustrating schuppen structure below the Glencoul Thrust.
A, Lewisian Gneiss ; Bg, dyke in gneiss ; Ca, Basal Quartzite (Cambrian) ; Cb, Pipe Rock ; Cc, Fucoid Beds ; Cd, Salterella Quartzite ; Ce, Limestone (Cambrian) ; T.P. and t, thrusts. (After Peach and Horne, Geol. Surv.)

CHAPTER LXV

DEVONIAN

THE Devonian is the first of three Late, or Upper, Palaeozoic Systems. It takes its name from the county of Devonshire. Throughout most of Britain the Devonian is represented by a continental facies called Old Red Sandstone. By continental facies is meant any non-marine deposits, formed in lakes or on dry land, whether transported by air or water.

We have now left behind us the great Caledonian Geosyncline. It was an Early Palaeozoic phenomenon, and, as already pointed out, passed out in the Downtonian. At the close of the Silurian its place was taken by the folded Caledonian Chain. The unconformity of various divisions of the Old Red Sandstone upon the contorted and denuded rocks of the Caledonian Chain is one of the most impressive geological phenomena in Britain. While the Caledonian Chain was folded and elevated, the platform to the south-east was also extensively upheaved. A continental area was thus produced, including northern Europe as far south as the subsequent Hercynian Chain, the northern front of which passes through Southern Ireland, South Wales, the Straits of Dover, Belgium and Germany to Poland (Fig. 308).

North of the Hercynian front just indicated the Devonian is mainly continental; south of it, mainly marine (Fig. 293). In fact the Hercynian Chain was preceded by the Hercynian Geosyncline.

CONTRASTED FACIES.—Let us now briefly contrast the two facies of the Devonian, found respectively north of, and within, the Hercynian Geosyncline.

(1) Continental Facies or Old Red Sandstone. The continental is the only facies that occurs in Scotland. In England it extends south to the Bristol Channel. Its characteristic rock types are conglomerate, red sandstone, flag, red marl, and unfossiliferous concretionary limestone called cornstone; we have already compared cornstone with the kankar concretions that grow to-day in certain subsoils of India and Africa subjected to alternate wet and dry seasons. Its characteristic fossils are fresh-water fish in the broad sense, eurypterids, water fleas (*Estheria, cf.* Fig. 157), terrestrial myriapods, and land and water plants.

(2) Marine Devonian. In Britain the marine facies is only exposed in the Devonshire peninsula. Its characteristic rock types are sandstone, shale

and fossiliferous bedded limestone. Its characteristic fossils are brachiopods, trilobites, corals, stromatoporoids, etc. (Fig. 298).

Correlation between the two facies of the Devonian is achieved by paying attention to the position of the rocks in reference to other systems. Each in its own district, the continental and marine facies of the Devonian can be found interstratified with conformable contacts between the Silurian and the Carboniferous. They are therefore in a broad sense time-equivalents of one another.

As most of the Devonian of Britain is of the continental facies, called Old Red Sandstone, we shall give this our first attention.

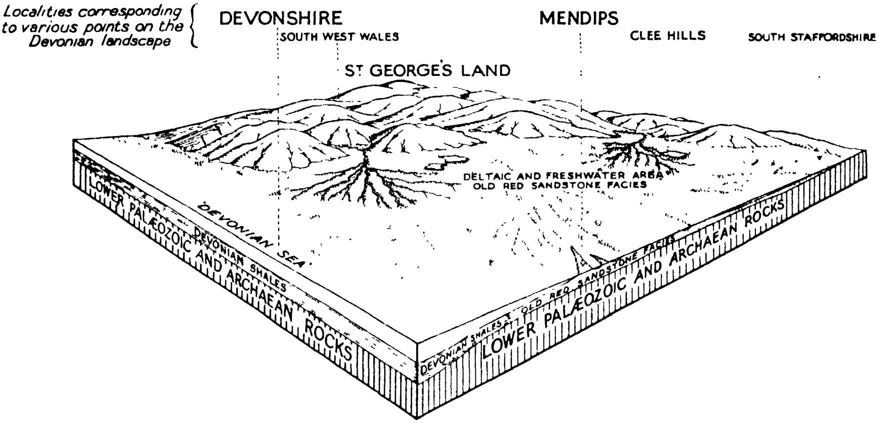

FIG. 293. Block-diagram to illustrate the conditions under which the lower part of the Old Red Sandstone deposits are thought to have accumulated. (After Edmunds and Oakley, Geol. Surv.)

OLD RED SANDSTONE

There are three great divisions of the Old Red Sandstone in the British Isles, each distinguished by its lithological types and fossils.

One of these divisions rests unconformably upon either of the other two, according to district. Therefore by the Law of Superposition it is later than the other two. It is called the Upper Old Red Sandstone.

The other two divisions present a problem. The one occurs in England, Wales, Ireland and the southern half of Scotland, the other in the northern half of Scotland. They are nowhere known to occur together. Therefore their relative ages cannot be established by the Law of Superposition. As already indicated, their fossils are different; but then their fossils are mostly fresh-water fish, and to-day in Africa, for instance, different drainage basins have different fish. Accordingly it was claimed for a time that the two formations were of the same age. Presently, however, it was pointed out that their plants, as well as their fishes, are different. This certainly proves a difference of age, since plants can easily migrate across a narrow watershed. Once it is admitted that the southern and northern formations are not contemporaneous, it is clear that the southern formation must be the earlier, because, on the English-Welsh border and at Lesmahagow in Lanarkshire, it rests conformably on the Downtonian, with obvious faunistic connection. If the northern formation were older than the southern, it would therefore have to be at least as old as the Downtonian; but the evolutionary stage of its fossils rules out any such suggestion.

To sum up: There are three divisions of the Old Red Sandstone in the British Isles:

Upper, developed indiscriminately both in the north and the south
Middle, developed in the north
Lower, developed in the south

We may now consider them in more detail, beginning with the oldest.

LOWER OLD RED SANDSTONE.—The main British outcrops of Lower Old Red Sandstone occur in Herefordshire, the Cheviots, the Midland Valley of Scotland, Lorne, Ben Nevis, Glen Coe and many parts of Ireland.

The commonest sediments are brown-red or chocolate-red sandstone (brownstone), often with conglomerate. Cornstone is well developed in Herefordshire.

Vulcanicity was very widespread in Scotland, with production of basalt, andesite and rhyolite lavas in such districts as the Cheviots, Pentlands, Ochils, Lorne, Ben Nevis and Glen Coe. Most of the great granite intrusions of the Lake District, Cheviots, Southern Uplands and Highlands are of this date. The cauldron subsidences of Ben Nevis and Glen Coe are particularly interesting. Here are the main features of the geology of Ben Nevis, illustrated with map and section (Fig. 294).

The country rock consists of schists. These latter are pierced by a boss of granite called the Outer Granite. This in turn is cut by a swarm of parallel north-east porphyrite and lamprophyre dykes (which extend away from the granite much more continuously than is shown in the figure). The Outer Granite is pierced by a smaller boss of granite, which cuts off the dykes and is called the Inner Granite.

The Inner Granite surrounds, and chills against, a down-faulted cylinder of andesitic lavas and ashes, that rest unconformably on schist. These down-faulted central volcanic rocks represent a subsided portion of the roof of the Inner Granite. As they slipped down from relatively cool upper regions into the still molten Inner Granite, they brought their low temperature with them, and so chilled the granite magma at its contact into fluxion rhyolite. Exteriorly the same magma crystallized unchilled.

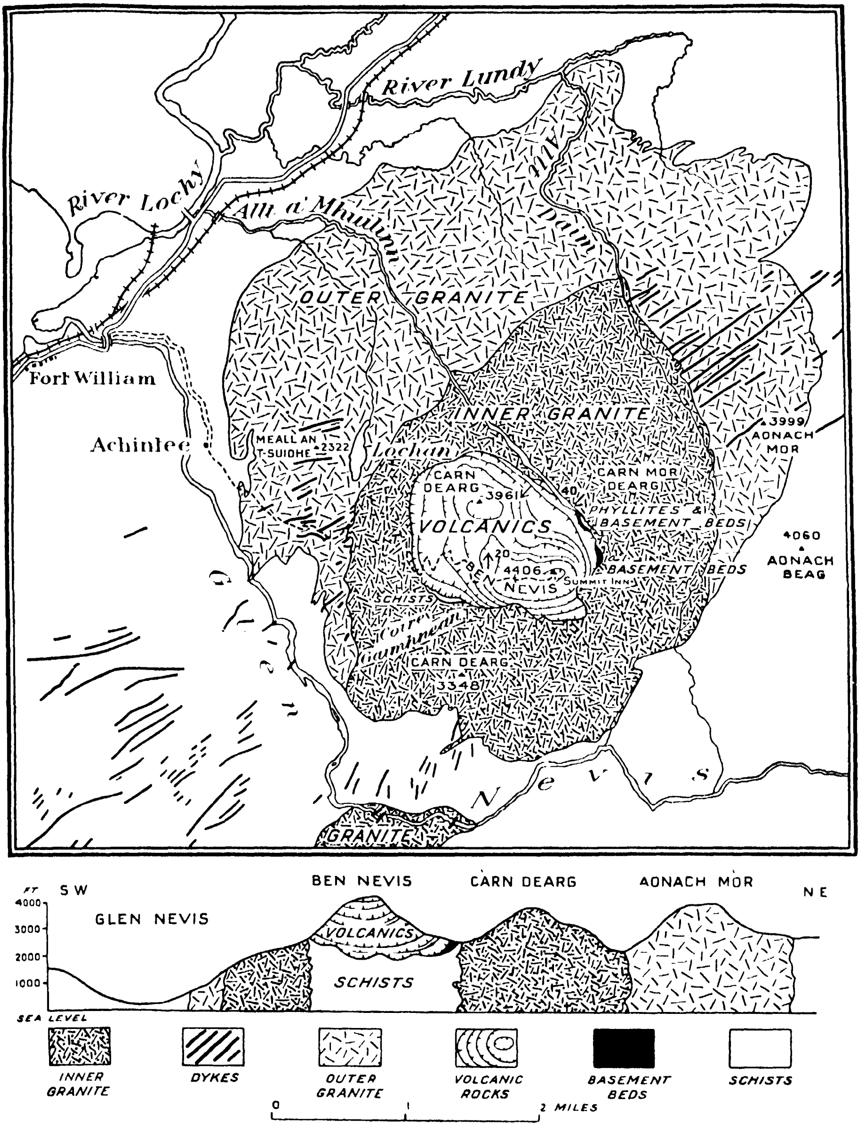

FIG. 294. Map and section of Ben Nevis. (After Maufe, Geol. Surv.)

Where a cylindrical mass of rock has subsided in this fashion, bounded by a circumferential fault, the result is called a *cauldron subsidence*. Such a cauldron subsidence may, or may not, affect the surface (Fig. 108). In the former case the cauldron subsidence is described as subaerial, in the latter as subterranean. It is thought that the granite bosses of Ben Nevis have filled subterranean cauldron subsidences, which did not extend to the surface, but retained, as it were, lids of country rock (large-scale stoping of Chapter XLI).

The principle of a dyke swarm has already been explained (Chapter XLI). Each of the Ben Nevis dykes fills a crack developed by tension. The cracks were located by the presence of granite magma at lower levels within the Ben Nevis pipe than that occupied by the already consolidated Outer Granite. In fact the crust had been almost completely perforated at Ben Nevis before the dyke-cracks formed ; and each new crack, due to extraneous tension, tended to be developed through the pre-existent perforation. Presently the directed tension of the dyke phase disappeared, and the Ben Nevis pipe for a time resumed its rôle as a site of cauldron subsidence. The Inner Granite rose to fill a subterranean cauldron, while the central lavas mark the sunken floor of a subaerial cauldron developed contemporaneously.

The so-called fishes of the Lower Old Red Sandstone were many of them ostracoderms like *Pteraspis* and *Cephalaspis* (Figs. 201, 202), but others were primitive sharks. Eurypterids were represented by *Pterygotus,* a genus surviving from the Silurian (Fig. 162). Myriapods occur. Plants include many land forms (Fig. 252).

MIDDLE OLD RED SANDSTONE.—The Middle Old Red Sandstone of Britain is only found in the region of the Moray Firth and the Orkneys, where it rests unconformably on the Highland Schists and associated granites. The most typical sediment is flagstone, frequently suncracked, showing that the waters in which it was deposited often dried up (Fig. 16). One is reminded of the marginal portions of Lake Chad, or of certain coastal lagoons, confined by spits or bars.

The fishes of the Middle Old Red Sandstone were made famous by Hugh Miller. Some are armoured, as *Coccosteus* and *Pterichthys.* Others are lung fish, as *Dipterus* (Fig. 295). The curious little *Palaeospondylus* was probably not a true fish, but a cyclostome (Fig. 203).

At Rhynie, south of Huntly in Aberdeenshire, a peat of this age has been silicified, presumably by a hot spring, and has preserved the minutest details of a few species of land plants (Fig. 253), as well as the earliest insect known to Science. There is a wonderful series of slices of this deposit in the Botanical Department of Glasgow University, presented by Dr. Kidston, who was largely concerned with its investigation.

UPPER OLD RED SANDSTONE.—The widespread Upper Old Red Sandstone of Britain is everywhere, except perhaps in Shetland, unconformable : it rests, according to locality, on Middle or Lower Old Red Sandstone, or on still older rocks. Discordance between Upper and Middle Old Red Sandstone is very clear both in the Orkneys (Hoy) and in the Moray Firth region. Discordance between Upper and Lower Old Red Sandstone is a feature of

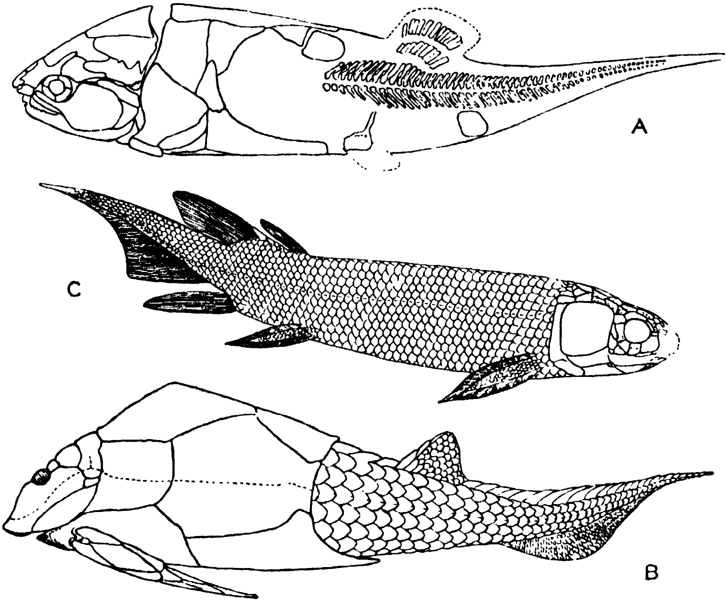

FIG. 295. Middle Old Red Sandstone fish. (After Watson in Geol. Surv.)
A. *Coccosteus decipiens* Agassiz, length 13 inches.
B. *Pterichthys milleri* Agassiz, length 8 inches.
C. *Dipterus valenciennesi* Sedgwick and Murchison, length 8 inches.

the Midland Valley of Scotland, and is particularly well seen at Arbroath, on the east coast (Fig. 296), and north of Cardross on the Clyde. On the borders of England and Wales the contact of Upper and Lower Old Red

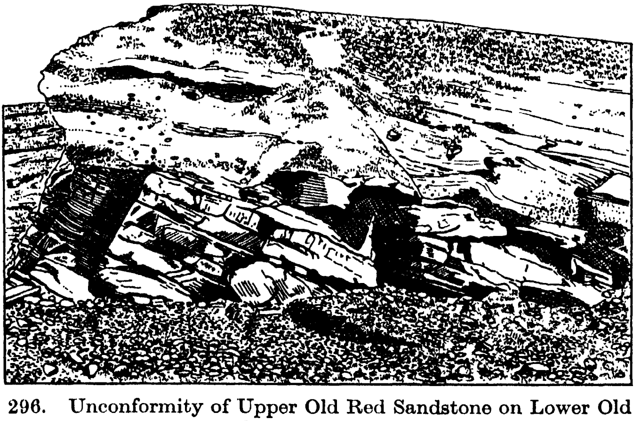

FIG. 296. Unconformity of Upper Old Red Sandstone on Lower Old Red Sandstone, Arbroath. (Geol. Surv. photo.)

Sandstone is a disconformity, the importance of which would be difficult to appreciate without reference to Scotland.

Bright red sandstone and quartz-conglomerate are characteristic sediments at the bottom of the Upper Old Red Sandstone. Pink, white and yellow sandstones, with cornstone concretions (in Scotland), are characteristic at the top. The formation is linked by passage beds with the Carboniferous.

Holoptychius is a characteristic fish (Fig. 209B). Land plants and a freshwater mussel have also been found (Fig. 297).

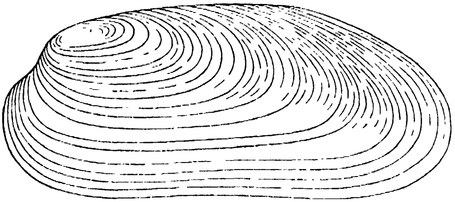

FIG. 297. Upper Old Red Sandstone freshwater mussel. (After Geol. Surv.) *Archanodon* (*Amnegenia*) *jukesi* (Forbes), × ½.

VERTEBRATE FOSSILS.—Although fish were so abundant in Devonian times that the period is often called the Age of Fishes, the common bony fish of to-day, such as cod and trout, had not yet started. The characteristic types are Crossoptérygii, sharks, lung fish, and the wholly extinct armoured 'fish' known as ostracoderms. As explained in Chapter XLIX, the ostracoderms are so primitive that they can only be spoken of as fish in a rather loose sense.

An advance towards man is recorded by amphibian remains in East Greenland.

MARINE DEVONIAN

Marine Devonian is well represented in Devonshire. Among other formations is an important limestone at the top of the Middle and bottom of the Upper Devonian. To it is largely due the beauty of Plymouth. Volcanic rocks, including pillow lavas, occur in association with the marine sediments; but the granites of Cornwall and Devon are altogether later.

FAUNA.—Graptolites are only represented by dendroid forms, such as *Dictyonema* (*cf.* Fig. 283B).

Trilobites are greatly reduced in variety; *Phacops* is a good example (*cf.* Fig. 288B).

Brachiopods are important: *Lingula* among the hingeless forms is apt to occur with brackish associates. *Spirifer* is abundantly developed among the hinged forms (Fig. 298A).

Corals are numerous: *Heliolites* (Fig. 298D), *Favosites* (*cf.* Fig. 288E) and the remarkable *Calceola* (Fig. 298C).

Bryozoa: *Fenestella* (*cf.* Fig. 168).

Hydrozoa: *Stromatopora* is a limestone-builder at Plymouth (Fig. 298B).

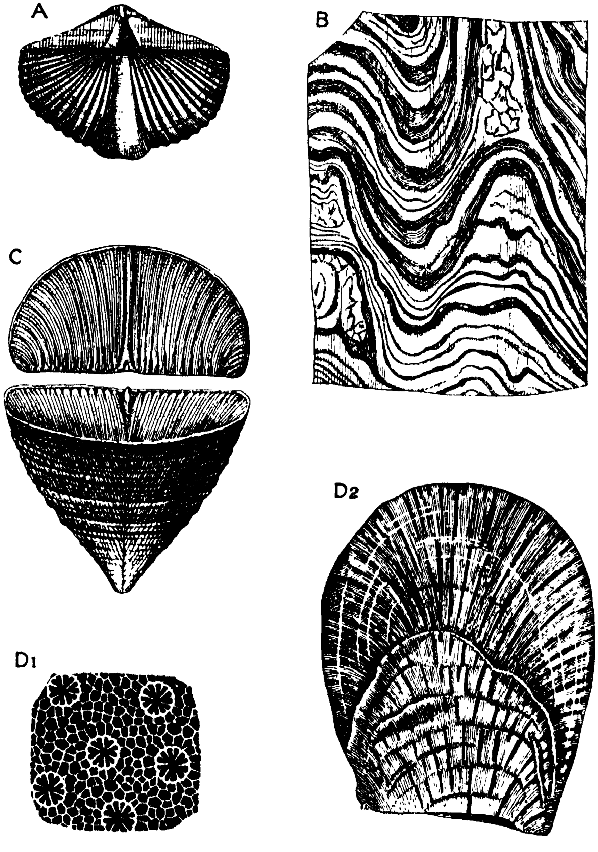

Fig. 298. Marine Devonian brachiopod, hydrozoan and corals. (After Geol. Surv.)

A. *Spirifer* cf. *cuspidatus* Schnur, × ¼; B. *Stromatopora concentrica* Goldfuss, × ½; C. *Calceola sandalina* Lamarck, × ½; D. *Heliolites porosus* (Goldfuss); D1, transverse section, × 2; D2, longitudinal section, × ½.

Crinoids are less abundant than in Silurian.

Cephalopods: *Orthoceras* in a broad sense continues, and in Europe goniatites are important.

Fish occur, but not nearly so prominently as in the restricted fauna of the Old Red Sandstone.

STRUCTURE AND ECONOMICS

STRUCTURE.—In describing the mutual avoidance of the Lower and Middle Old Red Sandstones of Britain, we have referred to their southern and northern fields of distribution. If we take the whole European foreland of the Hercynian Chain (Fig. 308) into consideration, we find that it is more a matter of west and east than of south and north. Marine Lower Devonian is not known with certainty from this foreland, though a bore at Little Missenden in Buckinghamshire and some erratics from the floor of the Baltic suggest that its bottom beds may locally be represented. Continental Lower Devonian is almost restricted to Ireland, Wales, England and Southern Scotland (we are not considering Spitzbergen). East of this it has only one small outcrop in Norway. Marine Middle Devonian is found transgressing the foreland in Belgium, and also resting on transgressive continental Middle Old Red Sandstone over a wide area of the Baltic provinces and Russia. Middle Old Red Sandstone occurs, in addition, in North-East Scotland, and reappears on the opposite coast of Norway. As the development and preservation of even continental sediments is greatly aided by subsidence, the facts just enumerated point to the Hercynian foreland having experienced a see-saw motion during Lower and Middle Old Red Sandstone times, first down towards the west, then down towards the east.

When we turn to local detail perhaps the most interesting structural features, apart from cauldron subsidences, are found in the Midland Valley of Scotland. This so-called valley is really a diversified lowland tract that can be traced from coast to coast of Scotland to reappear in the North of Ireland. In Scotland it is bounded either side by north-east faults, near which the exposures are mainly Lower Old Red Sandstone, thrown down with reference to the rocks outside, and passing interiorly under Upper Old Red Sandstone and Carboniferous. The tectonic history of the Midland Valley is complicated in the extreme, beginning at least as early as the Ordovician, and continuing after the Carboniferous. Here we have only space to refer to one structural element, the Highland Border Fault, which in most of its outcrop separates Dalradian and Cambro-Ordovician rocks on the north-west side from uptilted Lower Old Red Sandstone on the south-east. The latter consists near the Border of immensely thick conglomerates, which have derived their pebbles from the Highlands, and thin away in the opposite direction. The Highlands must have been rising relatively to the Midland Valley to furnish so thick a fringe of gravel.

The movement that accompanied the formation of the Lower Old Red Sandstone continued, or was renewed, at a later stage. As already remarked, the Old Red deposits are steep along the fault. In fact they are sometimes vertical, or even slightly overturned, at close quarters to the dislocation, and may maintain dips of over 45° for as much as 3 miles from the same. It is

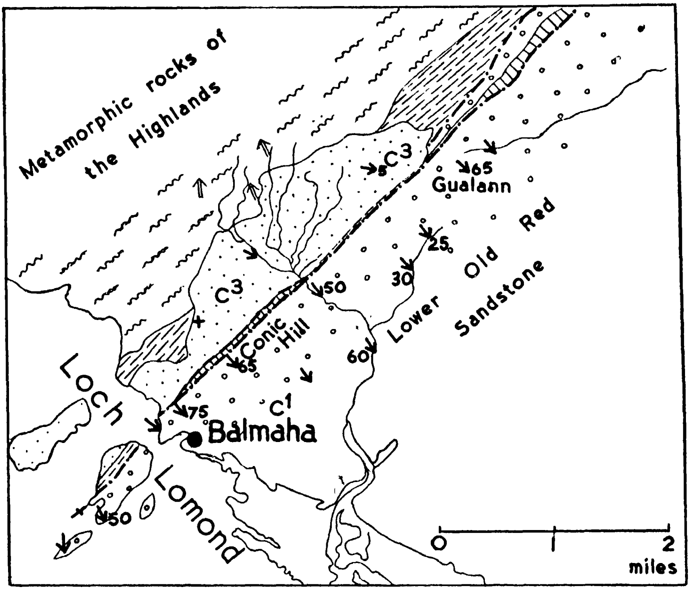

FIG. 299. Highland Border geology at Balmaha. Wavy lines, Highland schists; dashes, Highland Border series; small circles, Lower O.R.S.; dots, Upper O.R.S.; thin bands with cross lines, serpentine; heavy dash-and-dot lines, faults. (After McCallion.)

clear that the movement involved must have been of a compressive type; and the boundary fault to-day, though nearly vertical, is at places definitely reversed.

The Highland Border Fault for some 20 miles, where it crosses Loch Lomond, is double and includes between its two branches a nearly vertical

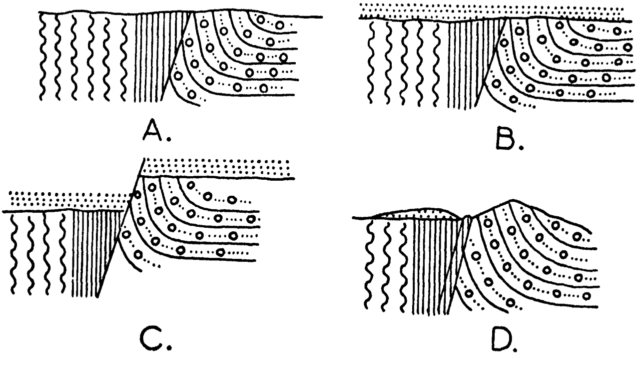

FIG. 300. Evolution of Highland Border structures at Balmaha, *see* Fig. 299. (After McCallion.)

sheet of Ordovician serpentine, with a cross measurement of 50 yards or so (Fig. 299). For some 10 miles this serpentine is in the wonderful position of separating steeply tilted Lower Old Red Sandstone conglomerates on the south-east, from flat-lying Upper Old Red Sandstone and Carboniferous, resting upon steep Cambro-Ordovician and Dalradian, on the north-west.

The explanation may be expressed in three stages as follows :

(1) Steep thrust faulting before Upper Old Red Sandstone times carried Highland rocks up and forward against tilting Lower Old Red Sandstone conglomerates. The Highland formations adopted, or maintained, a steep attitude during this movement, and their marginal member at the close was a thick sheet of Ordovician serpentine, a notoriously slippery rock (Fig. 300A).

(2) Erosion smoothed down the fault ; and on the levelled surface, Upper Old Red Sandstone accumulated, followed by Carboniferous. The Upper Old Red Sandstone lay equally on the Highland rocks, including the serpentine, on the one side, and on the Lower Old Red Conglomerates, on the other (Fig. 300B).

(3) In post-Carboniferous times tensional stresses supervened. The old wound reopened, but on the north-west instead of the south-east side of the slippery serpentine. The fault zone, now reacted as a normal fault, and, with its inclination towards the Highlands, inherited from its early overthrusting history, located a downthrow in that direction (Fig. 300C). Then once more came erosion (Fig. 300D).

Passing over other instances of the same kind, we can only in this brief summary recall that the Lower Old Red Sandstone of Britain is generally very much less moved than the Silurian of the Caledonian belt—though conformable to Downtonian in parts of the Midland Valley and the Welsh Mountain borderland. Only at one locality, Anglesey, has Caledonian cleavage been developed.

The marine Devonian of the geosyncline is folded, overthrust and cleaved, along with its associated Carboniferous, in the much later development of the Hercynian Chain.

ECONOMICS.—While slates cease in non-Hercynian Britain with the end of the Silurian, building sandstones may be said to start. Most of the building sandstones of Britain are either of Old Red Sandstone, Carboniferous or New Red Sandstone age : sandstones earlier than the Old Red Sandstone are generally of the greywacke and quartzite types and too hard to be of much value ; sandstones later than the New Red Sandstones are generally but little cemented and therefore too soft.

Flags from the Middle Old Red Sandstone of Caithness were tremendously quarried until towns began to pave with concrete.

Granites are important in Scotland and at Shap in the North of England.

Porphyries are worked for setts on Loch Fyne.

Lavas for road metal at Edinburgh.

REVIEW OF BUILDING STONES IRRESPECTIVE OF AGE

Building Stones should be: strong; resistant to weather; not too pervious; easily dressed; present in bulk; convenient for transport; good looking.

Granite is used where strength is particularly important as in lighthouses or the Forth Bridge; also for decorative work; also for setts (Bonawe). Other rocks commonly used for setts are porphyry (Loch Fyne) and dolerite (Kilsyth).

Sandstones and limestones are more used for ordinary building than are igneous rocks. They are more easily worked, and in this matter their bedding often helps. Sandstones with siliceous cement weather well, but may be too hard. Ferruginous cement weathers well. Calcareous cement weathers badly, especially in towns. In building, bedding should be placed at right angles to the weathering surface, or the stone will scale.

British freestones are generally either sandstone or oolitic limestone, the latter well developed in the English Jurassic. Chalk also furnishes freestone, but is too easily weathered except for interiors.

CHAPTER LXVI

CARBONIFEROUS

THE Carboniferous System derives its name from the carbon of coal, of which it is the chief repository, not only in Britain, but also in the world at large. The English development is split, according to lithology, into three main divisions :

Coal Measures
Millstone Grit
Carboniferous Limestone

An International Congress has proposed to give these divisions palaeontological definition under the titles :

Westphalian, with perhaps Stephanian at the top
Namurian
Dinantian (Tournaisian followed by Viséan)

Dinant, Tournai, Visé and Namur are all Belgian towns ; Westphalia a German province, rich in coal. Stephanus is the Latin form of Étienne, and St. Étienne is a town in the Central Plateau of France.

Connected with the palaeontological classification there is, as might be expected, discussion as to the best boundary between Dinantian and Upper Devonian. There is also lack of agreement as to the status of Stephanian. Some regard this latter as a thoroughly continental facies—equivalent of Upper Westphalian ; others as an independent time-division, curtailing the scope of Upper Westphalian. These are matters of detail that need not trouble a beginner.

It is a long established custom to class the Dinantian as Lower Carboniferous, and the Namurian and Westphalian as Upper Carboniferous. Even in this matter there is difference of practice, for some prefer to follow Kidston and divide the Namurian between the Lower and Upper Carboniferous, where a drastic change of flora is registered in the Scottish record. The remainder of the present chapter is devoted to the British development of the Lower Carboniferous, in the traditional sense of the term. The treatment, though very condensed, is fuller than in other stratigraphical chapters of this short account. The excuse may be offered that in education it is often more important to pursue principles than to acquire knowledge. The Lower Carboniferous of Britain affords an ideal hunting ground for stratigraphical principles.

CARBONIFEROUS LIMESTONE (DINANTIAN)

The Carboniferous Period started, or followed closely upon, a great marine transgression, which took the sea far north beyond the Hercynian Geosyncline over wide spreads of Upper Old Red Sandstone. In our hurried presentation we must anticipate the findings of research in regard to the palaeogeography of the time (Fig. 301). The south of Ireland and the Devon peninsula belonged to the Hercynian Geosyncline. To the north the first overflowing of this geosyncline inundated a neighbouring coastal platform including the greater part of Ireland, South Wales, Somerset, Gloucestershire, the Severn Valley to Titterstone Clee, Kent, as proved by boring, Boulogne and Belgium. North of this, from the Wicklow Mountains eastwards, lay land of varying elevation and persistence, extending to begin with to what we may call the Border Trough, that embraced much of Northumberland. The southern portion of this land, reaching from the Wicklow Mountains across St. George's Channel, and thence through the heart of Wales and the English Midlands into Brabant in Belgium, maintained itself above water for particularly long ; in fact it was not completely covered beneath accumulating sediment until much later than Coal Measure times. Its western section has been aptly called St. George's Land. Before long, perhaps even at the very beginning of the period, the Carboniferous sea circumvented St. George's Land and entered a gulf or strait, known as the Lancashire Trough. Lakeland and the Fell Country beyond Craven still for a time remained dry land, North-England, until about half-way through the Carboniferous Limestone epoch of submergence. To the north of the Border Trough lay yet another temporary island, the Southern Uplands, that in the west remained unsubmerged until Coal Measure and even New Red Sandstone times. Beyond stretched still another depression, the Midland Valley Trough, bounded on the north by a great mass of land, which may be termed for short the Scottish Continent.

The islands between the Hercynian Geosyncline and the Midland Valley Trough were relatively low and small, and did not contribute much terrigenous sediment during Carboniferous Limestone times. In fact the Carboniferous Limestone may be viewed as a clear-water platform-facies fringing St. George's Land, the Mercian Highlands and Brabant. It had a southern and northern development meeting in Ireland round the termination of St. George's Land. This platform-facies had wide variety of reef, bank and lagoon, recalling features of the modern Great Barrier Reef of Australia and of the Great Bank of the Bahamas. The range of conditions in such situations is very marked, and it is not surprising to find a corresponding variety in the faunal composition of the Carboniferous shelf-limestone facies. In fact, some beds are unfossiliferous. If space permitted much might also be said of lithological variations. Oolite and dolomite are both well represented. The latter introduces a particularly complex subject, since some of the dolomites of the Lower Carboniferous are original, while others are due to alteration of limestone, penecontemporaneous or long subsequent as the case may be. Corals such as *Lithostrotion* (Fig. 304) often built extensive reefs suggesting seas of tropical warmth ; but there is little evidence that these particular reefs had the capacity of keeping pace with progressive subsidence, in the manner invoked in Darwin's theory of present-

FIG. 301. Great Britain in Lower Carboniferous times.

day atolls. On the other hand associations of certain brachiopods, lamellibranchs and bryozoa, and of the particular coral genus *Amplexus*, did possess this faculty, and in many situations, at various stages of Lower Carboniferous times, built up reef-knolls, as they are called, which managed for long intervals to keep their heads in aerated wave-tossed surface waters.

Geographical accident and bulk of development have combined with beauty of field display and fossil content to exaggerate in English eyes the importance of shelf-, or platform-limestone in Lower Carboniferous stratigraphy. Comparable limestones of pre-Carboniferous date are much more restricted in the British Isles, except in the case of the Durness Limestone on the north-west margin of the Caledonian Geosyncline ; and the Durness Limestone suffers alike from inaccessibility and from scanty preservation of its fauna. This latter reproach cannot be brought against the Wenlock and other Silurian limestones that border the Caledonian Geosyncline on the south-east, or against various Ordovician and Devonian Limestones that, under appropriate conditions, have formed at times within geosynclinal boundaries ; but none of these compares in thickness or extent with the great Carboniferous Limestone. It is, however, necessary for British geologists to take into consideration two other facies in the Lower Carboniferous of their country, which may be summarized briefly under the titles goniatitic and deltaic.

The goniatitic (often called culm) facies of the Carboniferous is equivalent to the graptolitic facies of the Ordovician and Silurian. The goniatites are found in black shales or thin-bedded black earthy limestones, and are accompanied by a special fauna, for the most part thin-shelled lamellibranchs, such as *Posidonia* [*Posidonomya*]. Radiolarian cherts are fairly commonly interbedded with goniatitic shales. The radiolaria of these cherts lived near the surface ; their concentrated deposition merely denotes a quiet bottom, where the chemistry was inimical to an ordinary shelly fauna. The goniatites are variously interpreted as surface or bottom dwellers. The associated thin-shelled lamellibranchs are usually accepted as bottom forms adapted to a quiet and chemically unattractive environment. As an alternative it may be suggested that some of the lamellibranchs floated attached to seaweed, but this leaves unaffected the inference concerning the nature of the bottom.

Thus the goniatitic facies denotes still bottom-waters, with a comparatively unaërated composition, unfavourable to the life of corals or hinged brachiopods. It cannot be too clearly stated that the goniatitic facies of the Carboniferous is not synonymous with a shale or mudstone facies. Many shales and mudstones contain a fauna that links them naturally with the shelf limestone. It is obvious that some feature additional to the mere presence or absence of mud, such for instance as aëration, played a decisive part. In many cases it is certain that a goniatitic intercalation in shelly or deltaic accumulations was deposited in water of very moderate or even quite shallow depth ; but a succession of goniatitic zones of small thickness may well have collected on a deep bottom. In the Hercynian Geosyncline, graded greywackes have been found along with goniatite shales. The matter requires further investigation, but the suggestion may be repeated that geosynclinal graded greywackes often represent sand and mud carried out by tunamis and then allowed to settle through still bottom-water.

The deltaic facies is very varied in its features. It contains a large proportion of terrigenous material, often including current-bedded well-washed sandstone. Its special fauna is lagoonal, estuarine or terrestrial. Its flora, as preserved to us, is mainly terrestrial, either drifted, or grown *in situ* and represented by coal seams seated on rooty fireclay or ganister. The deltaic facies of the Carboniferous gives many examples of rhythmic deposit with a marine limestone or shale, which may be brachiopodic or goniatitic, followed by unfossiliferous shale, sandstone, fireclay, coal. This rhythm is interpreted as due to intermittent rapid subsidence that repeatedly introduced sea conditions followed by shoaling and growth of swamp vegetation. The rhythm is often interrupted or imperfectly expressed, but there can be no doubt of its reality.

Just as might be expected from our experience of Ordovician and Silurian time-tables, based here on shells, there on graptolites, we find some difficulty in adjusting the age equivalence of the various stages of the two contrasted marine facies of the Carboniferous, brachiopodic and goniatitic. The complete solution will eventually be attained by critical study of interstratification. To-day the standard time-scale of the Lower Carboniferous is based upon Vaughan's researches in the Carboniferous Limestone of the Avon Gorge near Bristol. He divided the limestone into five main zones, which he named after certain representative fossils as follows :

Viséan	5. *Dibunophyllum*	D Zone
	4. *Seminula*	S Zone
	3. *Caninia*	C Zone
Tournaisian	2. *Zaphrentis*	Z Zone
	1. *Cleistopora*	K Zone

The K Zone belongs, perhaps, to the Devonian rather than the Tournaisian.

All the fossils mentioned in this list are corals except *Seminula*, now known as *Composita*, which is a brachiopod (Fig. 303). *Cleistopora* has changed its name to *Vaughania*, but its zone is still known as K (Fig. 304). Similarly the *Composita* Zone is still called S. Vaughan's zones are so frequently spoken of by their initials that anyone who tries to follow current research must be familiar with them in this guise. A helpful mnemonic is afforded by the two words *Kaiser ceased.* One misconception must be avoided from the start. The titular genera are not restricted to the zones named after them. For instance, *Zaphrentis* ranges up into and beyond the D zone. It was suited to a somewhat muddy environment.

With this introduction it is possible to give a brief account of the facies distribution in the Lower Carboniferous of our islands.

Devon and the extreme South of Ireland, owing to their geosynclinal situation, developed a succession unlike that of the rest of Britain, a succession moreover much disturbed by subsequent Hercynian movement, so that it is only partially understood at the present time. The Devon (and Cornwall) exposures show slates, greywackes, radiolarian cherts, thin-bedded dark earthy limestones and pillow lavas. Fossils are often scarce, but Lower Tournaisian has been identified by a shelly zaphrentid fauna, and Upper Viséan by a succession of deposits of goniatitic facies. It is commonly thought that there is a gap in the story due to unconformity ; but further work may well reveal the presence of thin intermediate zones hitherto overlooked.

When we leave the geosyncline, we find, south of St. George's Land, in South Wales, Somerset, Bristol and at intervals along the Severn valley, splendid exposures of the shelf-limestone facies. There is a widespread tendency to shale at bottom and top ; and in the Gower peninsula of Wales the Upper Shales are overlain by radiolarian cherts, classed by many with the Millstone Grit. Interesting migrations of coast line and consequent unconformities have been traced, especially at the junction of Tournaisian and Viséan. At Titterstone Clee and the Forest of Dean, in the Severn area, important sandstones form the top of the Lower Carboniferous sequence, so far as this is preserved. They begin in the C Zone at Titterstone Clee, but farther south in the Forest of Dean they do not start till the S Zone. They represent deltaic material from St. George's Land. On the whole there is very little evidence of volcanic activity, but pillow lavas and ashes are known in Somerset. Lavas also occur in Ireland near Limerick.

Earlier than S times most of Wales and the North of England, with the exception of the Lancashire Trough, was dry land right to the margin of the Border Trough. This latter, along with the Midland Valley Trough, received deltaic accumulations furnished by the Scottish Continent from the very beginning of the Tournaisian. The Lancashire Trough, separating St. George's Land from North-England, was entered by the sea, in either K or Z times, in the Tournaisian.

The Viséan of the northern coastal platform of St. George's Land is predominantly shelf-limestone, well displayed at Llandudno and in the dales of Derbyshire (S to D Zones). The Tournaisian of the Lancashire Trough farther north is mainly shelf-limestone. The succeeding Viséan is very muddy in composition, but it maintains an approach to shelf-limestone character until, in the D Zone, it becomes frankly goniatitic (Lower Bowland Shales). The Viséan of North-England starts as shelf-limestone (Great Scar

Limestone, upper C to lowest D zones), and continues upwards with repeated interbedding of shelf-limestone and terrigenous deltaic material (Yoredales, main part of D zone and later, typically developed in Wensleydale, in the upper reaches of the river Ure). The Yoredales register an intermittent advance of Scottish deltas into the otherwise clean sea that submerged North-England.

The junction between the Lancashire Trough and North-England is afforded by a belt of faults named after a Yorkshire district, Craven (Fig. 301). There can be no doubt that the Craven Faults were actively moving during Lower Carboniferous times : The Lower Carboniferous deposits to the south start earlier than to the north, and where contemporaneous, attain a much greater thickness and a much more argillaceous composition. Their fauna is different as befits muddy as compared with clear water ; and this difference becomes extreme when the Lower Bowland Shales with their goniatites and thin-shelled lamellibranchs are compared with the limestones of the Yoredales with their hinged brachiopods and corals. It is clear that the goniatitic Bowland muds collected on a relatively quiet deep bottom at the foot of a submarine scarp or slope, and that the Yoredale shelf-limestones grew in the waves farther up.

We have already mentioned reef-knolls keeping pace with subsidence. The classical instances in Britain border the Middle Craven Fault on its down-throw side. They were long ago correctly interpreted by Tiddeman. Several of the Craven reef-knolls have been etched out by present-day erosion, and stand 200–300 feet above the general level of the country-side, just as they did in the beginning above the local muddy, though not as yet goniatitic, bottom of the sea. Breccias associated with the reef-knolls have been recognised as products of landslipping and wave action. It remains to the future to settle how far the waves have been due to earthquakes. Very probably some of the unconformities that have recently been recognised in this region of special subsidence are connected with submarine earthquakes rather than with subaerial erosion. The occurrence of limestone beds composed of crinoid ossicles, broken shells and coral fragments in a muddy environment is suggestive.

Volcanic rocks are a very minor feature in the Mid-English Carboniferous. The best known are the toadstones of Derbyshire. They were named by early German prospectors, who found them *tod*, or dead, from the ore point of view. They consist of basalt, some with pillow structure. A basalt lava, with subaerially weathered top, has lately been recognised at Little Wenlock, Shropshire. Other volcanic outbursts are registered in the Isle of Man, and at Cockermouth on the north side of Lakeland.

The deltaic development of the Border and Midland Valley Troughs differs profoundly from the platform-limestone facies so well displayed in the greater part of England and Ireland. Sandstones and shales predominate, with several coals and few and thin intercalations of marine limestone, as compared with the massive limestone development elsewhere. One of the chief interests of the Scottish succession is the record it affords of the land plants and freshwater fish of the time. Moreover, as has repeatedly happened, from Devonian times onwards, Scotland was much more volcanic than England.

The main Scottish equivalent of the English Carboniferous Limestone is the Scottish Calciferous Sandstone Series, to which must be added the Lower Limestone Group of what is known as the Scottish Carboniferous Limestone Series. This last has three groups: the lowest, to which reference has just been made, undoubtedly lies near the top of the Dinantian (Carboniferous Limestone); while the middle group, possibly, and the top group, almost certainly, belong to the Namurian (Millstone Grit).

A comparative table for Scotland and England may be written, subject to future adjustment, as follows:

Scottish Millstone Grit		English Millstone Grit
Scottish Carboniferous Limestone Series	Upper Limestone Group	
	Limestone Coal Group	
	Lower Limestone Group	English Carboniferous Limestone
Scottish Calciferous Sandstone Series	Oil Shale Group	
	Ballagan Group	

As a rough approximation it may be said that the Ballagan Group ranges from K through C into S, and the Oil Shale Group from S into D, while the Lower Limestone Group represents the upper part of D. There is no positive evidence for K except the conformity between Carboniferous and Upper Old Red Sandstone referred to below.

The Ballagan Group is called after Ballagan Glen, north of Glasgow (Fig. 302). It consists mostly of shales and cementstones, but its uppermost member is the Spout of Ballagan Sandstone, over which a picturesque spout, or waterfall, leaps like a miniature Niagara. The Ballagan Group must begin at the very base of the Carboniferous for it is linked by intercalation of lithological types with the Upper Old Red Sandstone, locally fossiliferous. The Ballagan Group is called Tuedian in the Border Trough, since it is magnificently developed in the valley of the Tweed, where its top member is the widespread Fell Sandstone. The shales of the group are marly and grey-green or red and, with the interbedded cementstones, are scarcely fossiliferous, except for rare ostracods, lamellibranchs, the worm *Spirorbis*, fish and land plants. In Scotland even *Lingula* is very seldom found, but in the Cumberland portion of the Border Trough typical marine fossils are common. There can be no doubt that these shales and cementstones were deposited in lagoons subject to repeated concentration. Ripple marks, suncracks, occasional pseudomorphs after rock salt and fairly frequent gypsum fit with this explanation. Sandstones occur as interbeds, as well as appearing in force at the top of the succession.

The Oil Shale Group of the Lothians consists mainly of sandstones and marls with valuable beds of oil shale. Estuarine or freshwater ostracod-limestones are common, with the pure and extensive Burdiehouse Limestone, 50 feet thick, as the main example. The oil shales originated from carbonaceous brackish or freshwater muds, often containing fish remains and ostracods, and abounding in algae. Their contrast with coal is well shown by their place in the rhythmic sequence. In three cases oil shales overlie goniatitic beds and, in another case, the Burdiehouse Limestone. Coals are known in the Oil Shale Group of the Midland Trough, and are locally important (Scremerston Coals) in the lower part of the equivalent succession at Berwick in the Border Trough.

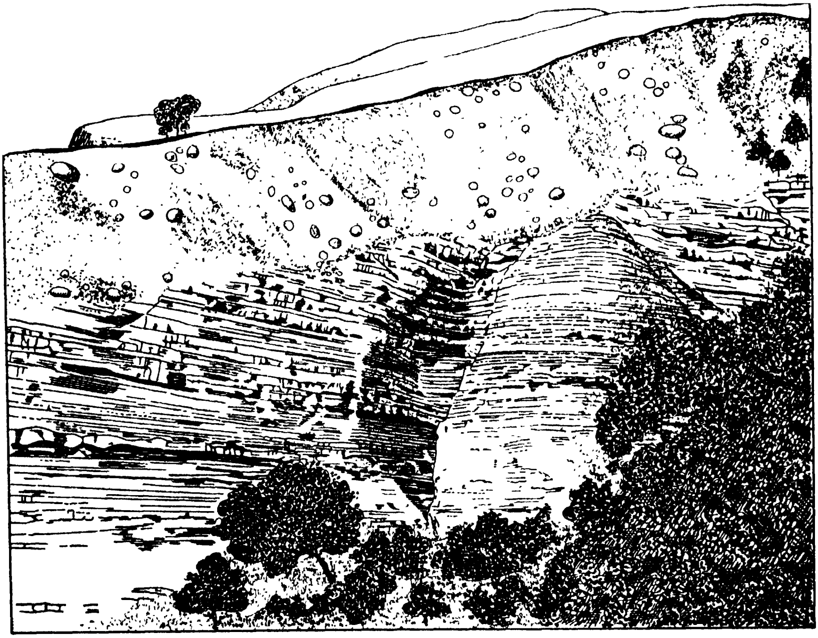

FIG. 302. Ballagan Beds in Ballagan Glen, near Glasgow. Note unconformable boulder clay.

Occasional beds of shelf-limestone appear in the upper part of the Oil Shale Group heralding the entry of the Lower Limestone Group. The corresponding development in the Border Trough tends to be more marine throughout.

The Lower Limestone Group of the Midland Valley consists mainly of dark shales with a few marine limestones of shelf type. The Hurlet Limestone, taken as the base, is named after a village near Paisley. It affords a typical example of Yoredale rhythm, for it overlies a substantial coal seam. The subsidence thus recorded was not quite abrupt, for a thin shale intervenes between the coal and limestone, and over wide areas shows a faunal succession from estuarine fish through lamellibranchs to brachiopods.

The Lower Carboniferous of Scotland contains volcanic rocks at many horizons. There is a widespread occurrence at the base of the formation in the Border Trough (Kelso and Birrenswark), but the main development, known as the Clyde Plateau Lavas, overlies the Spout of Ballagan Sandstone, though locally extending even on to Upper Old Red Sandstone.

The Clyde Plateau Lavas build a horse-shoe outcrop about Glasgow, and continue at great depth below the city. They are most conspicuous in the Campsie Fells, where in addition are many prominent necks, such as Dumgoyn (Figs. 34, 35). This last belongs to a discontinuous series strung along an east-north-east line from Dumbarton Rock on the Clyde to Fintry, and especially crowded along the north face of the Campsie Fells. The Dumbarton-Fintry necks furnished a particular type of basalt lava, and the resultant volcano ends 6 miles to the south-east, tapering out among other types of lava in the hills above Kilsyth. All this can be read from the one-inch Geological Survey map of the Glasgow district. Individual lavas of the Clyde Plateau group often had their tops weathered before being covered by the next flow, which tells us that the volcanic pile was mostly subaerial ; and, in keeping with this, interbedded sediment is very exceptional. The volcanic rocks are usually succeeded by sediments belonging to the upper part of the Oil Shale Group, greatly modified by volcanic detritus. In Ayrshire, however, a small area remained uncovered until Limestone Coal Group times.

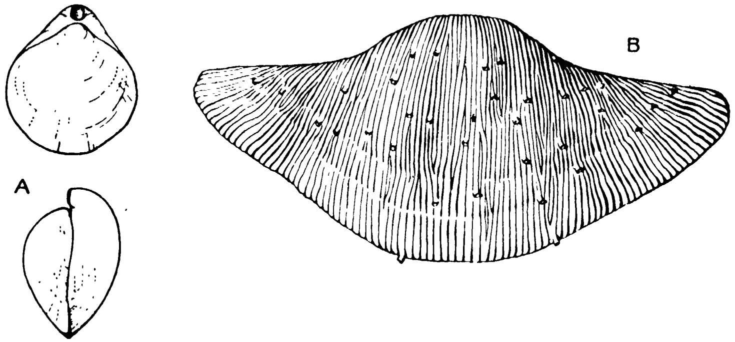

Fig. 303. Carboniferous Limestone brachiopods. (After Geol. Surv.)
A. *Composita* [*Seminula*] *ficoidea* (Vaughan), × 1 ; B. *Productus* (*Gigantella*) *latissimus* J. Sowerby, × 1.

The Clyde Plateau Lavas are sparingly represented as far west as Ballycastle in Ireland. In the east of Scotland their place is approximately taken by more isolated and probably rather earlier volcanoes at Arthur's Seat, Edinburgh (Fig. 101), and the Garleton Hills, East Lothian. The latter are particularly well known for the phonolitic laccolith of Traprain Law, the first pre-Tertiary phonolite to be recognised anywhere in the world. Previous to its discovery the great German school of petrologists had argued for a significant change in volcanic rocks beginning with the Tertiary.

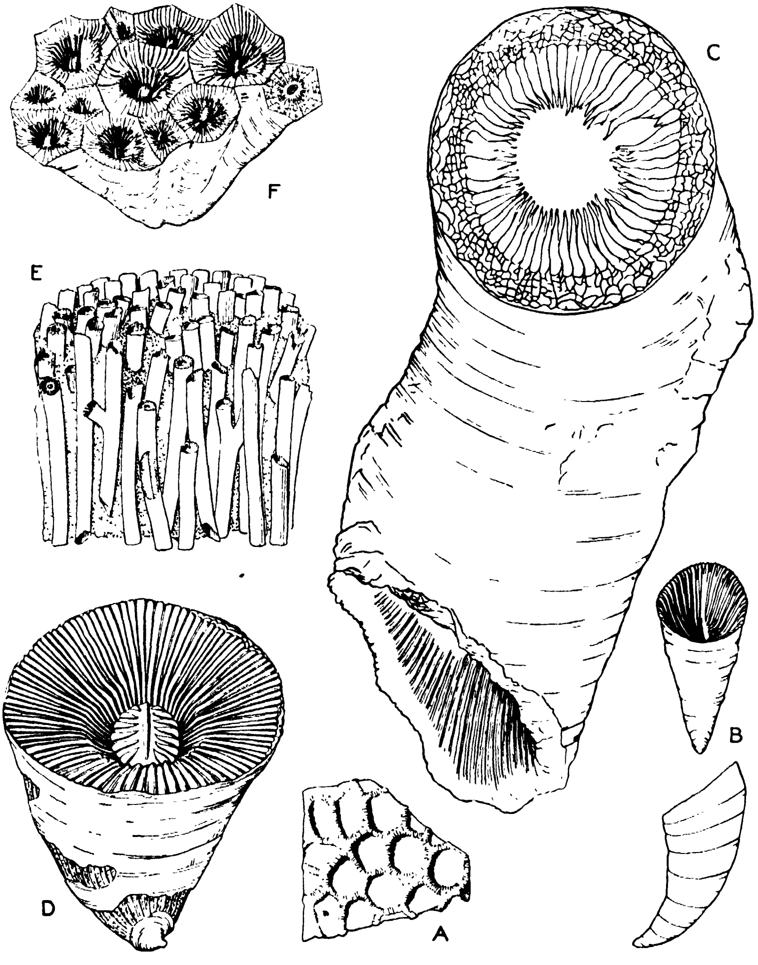

FIG. 304. Carboniferous Limestone corals. (After Geol. Surv.)

A. *Vaughania* [*Cleistopora*] *vetus* Smyth, × 1 ; B. *Zaphrentis konincki* Edwards and Haime, × 1 ; C. *Caninia gigantea* Michelin, × 1 ; D. *Dibunophyllum* cf. *turbinatum* (McCoy), × 1 ; E. *Lithostrotion junceum* (Fleming), × 1 ; F. *Lonsdaleia floriformis* (Martin), × 1.

LIFE.—Any geological museum in Britain is rich in characteristic fossils of the Carboniferous Limestone (Figs. 303, 304).

Brachiopods : *Productus, Spirifer, Composita* [*Seminula*], and in brackish mud facies, *Lingula* ; of these *Productus* is the most characteristic genus, and the large *Productus giganteus* does not continue beyond the Dinantian.

Bryozoa : *Fenestella* (*cf.* Fig. 168).

Lamellibranchs : *Aviculopecten*, and in the goniatitic facies *Posidonia.*

Gastropods : *Bellerophon* (Fig. 178), *Euomphalus, Pleurotomaria.*

Cephalopods : *Orthoceras*, coiled nautiloids, and in the proper facies goniatites of which the actual genus *Goniatites* ends with the Dinantian.

Corals : *Zaphrentis, Caninia, Lonsdaleia, Dibunophyllum, Lithostrotion*, the last essentially a Visean form.

Crustacea : Ostracods (*cf.* Fig. 158) and the trilobite *Phillipsia.*

Crinoids : Many forms.

Foraminifera : *Saccamminopsis.*

Fish : Sharks and in Scotland many estuarine or fresh-water forms.

Amphibia : Well represented in deltaic facies.

Plants : The Carboniferous Limestone on certain horizons has important developments of calcareous algae. The oil shales owe their nature mainly to non-calcareous algae. The coals are products of swamp vegetation, which though specifically distinct from that of the later Coal Measures described in the next chapter, is of the same general character.

CHAPTER LXVII

CARBONIFEROUS (*continued*)

MILLSTONE GRIT (NAMURIAN)

THE type region of the Millstone Grit lies in Lancashire and Yorkshire, where, in the Lancashire Trough (Fig. 301), the formation attains exceptional thickness. Both here and to the south the Millstone Grit presents a combination of deltaic and goniatitic facies. Rhythmic sedimentation is highly characteristic, though its details are not recognisable in Fig. 305. Each rhythmic recurrence tends to begin with goniatite shale, followed in turn by unfossiliferous shale, false-bedded grit or sandstone, seat-earth and coal, the last named of uneconomic thickness.

North of the Lancashire Trough, goniatitic intercalations seem to be replaced for the most part by beds containing hinged brachiopods, etc. Much of the story has still to be deciphered. On the one hand, the boundary of the Lancashire Trough appears to have been less definite than when the Craven Faults were functioning during Lower Carboniferous times. On the other, it is very exceptional to be able to trace an individual goniatite bed northwards into an individual brachiopod bed ; and allowance has to be made for disconcerting unconformities.

At the present time it is customary to adopt Bisat's classification and to recognise four major goniatite zones in the Millstone Grit, or more strictly three and a half. These follow upon the extinction of the genus *Goniatites* at the top of the Lower Carboniferous. The zones are often called by their initials: E, H, R, and lower part of G. The corresponding generic names are *Eumorphoceras*, *Homoceras*, *Reticuloceras* and *Gastrioceras* (Fig. 305). *Gastrioceras* ranges into the succeeding Coal Measures.

The general northward change of the Millstone Grit is well illustrated in Scotland. As indicated in the previous chapter, the two upper groups of the Scottish Carboniferous Limestone Series should, with varying degrees of probability, be reckoned along with the Scottish Millstone Grit as representative of the Millstone Grit Series of the English type area. These two so-called Carboniferous Limestone groups are probably sandier than the type Millstone Grit development, but their very minor marine intercalations are of brachiopodic character and are therefore more reminiscent of the type

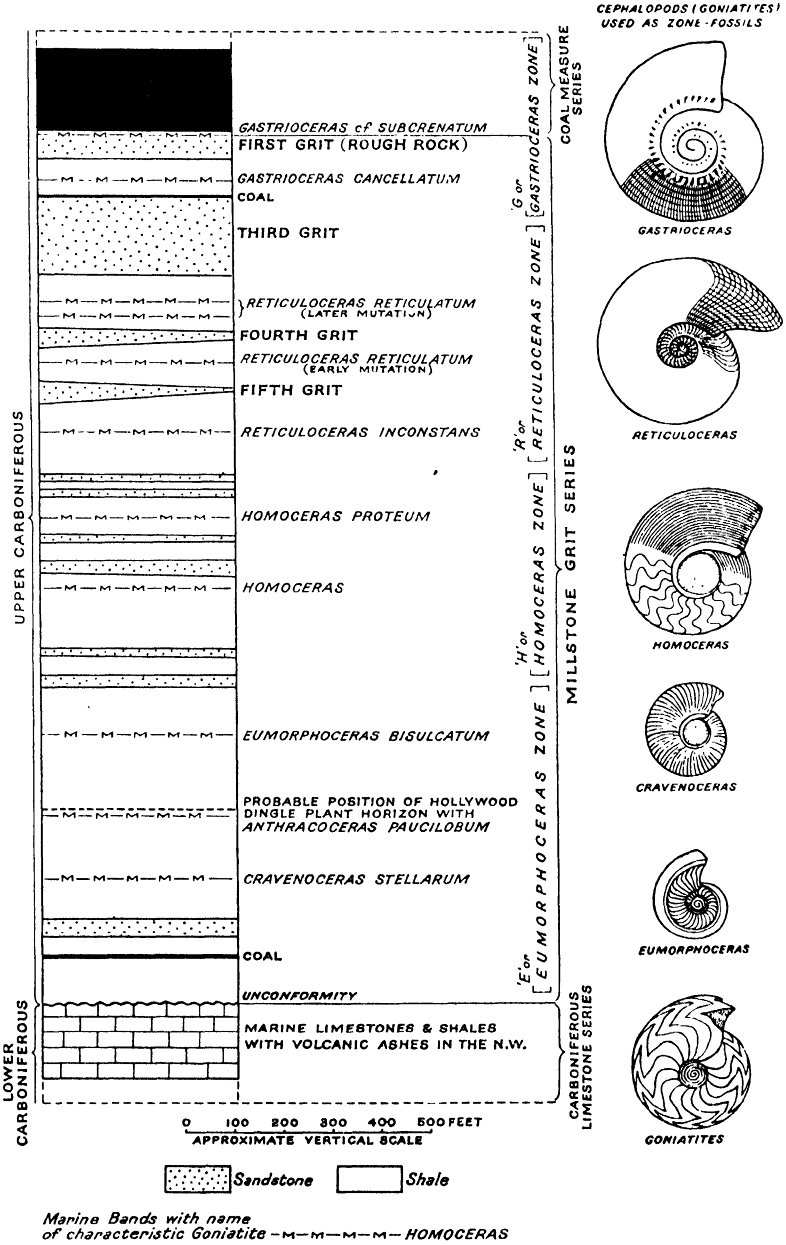

Fig. 305. Goniatite zones of Millstone Grit Series in North Staffordshire. (After Geol. Surv.)

Carboniferous Limestone than of the type Millstone Grit. The two are known respectively as the Limestone Coal and the Upper Limestone Groups.

The Scottish Limestone Coal Group consists of shales, sandstones, and fireclays, with valuable seams of coal and ironstone. The sequence is mostly non-marine.

The Scottish Upper Limestone Group is mainly composed of sandstones, sometimes gritty, with three or more thin marine limestones. The lowest of these is used to mark the base of the group. It is called the Index Limestone, because in boring it serves as a welcome indication that the Limestone Coal Group is just below. The Upper Limestone Group has yielded a very few goniatites referred to the E zone.

The Scottish Millstone Grit is a group of grits and fireclays, with very meagre marine beds in its lower part.

The correlations indicated above are in essence anything but modern. In 1899 W. Gunn compared the Scottish development with that of England and pointed out that the two upper divisions of the Scottish Carboniferous Limestone Series correspond with an assemblage which in Wensleydale, Yorkshire, lies above the Yoredale Beds as defined long previously by Phillips. He continued : ' The term Yoredale was by the Geological Survey extended so as to include these beds (in Yorkshire), but they were classed with the Millstone Grit by Phillips, though sometimes he seems to have included a portion of them in his Yoredale Series.'

Within the lower part of the Scottish Millstone Grit, at what is known as the Kidston plant break, there is registered an almost complete specific change in the composition of the land flora. A similar, but less closely located, break affects the estuarine fish fauna. Some attribute the apparent abruptness of the change-over to an unconformity. There certainly are minor unconformities connected with the Scottish Millstone Grit, as there are with other parts of the Scottish Carboniferous succession, but none seems important enough to meet the circumstances of the case. An alternative interpretation invokes migration dependent upon the geographical changes that are clearly recorded in the Millstone Grit of Britain and the Continent. According to this alternative the plant break of the Scottish Millstone Grit is due to replacement of the local flora when the spreading deltas of the Millstone Grit provided a highway for plant migration northwards from the growing Hercynian Chain. At the same time the Scottish rivers would become tributary to the general river system of Western Europe, thus opening their doors to migration of estuarine fish, hitherto debarred by the intervening Carboniferous Limestone sea.

In the Linlithgow district Scotland was volcanic at intervals throughout its Carboniferous Limestone epoch. The resultant basaltic lavas and ashes are occasionally interrupted by beds of marine limestone and other sediments. In Ayrshire the upper part of the Scottish Millstone Grit is represented by terrestrial outflows of basalt. These were exposed at the surface for a long time, and subjected to lateritic weathering, until eventually covered by the succeeding Coal Measures. As a result they are overlain by a valuable refractory clay, partly residual, partly detrital, which is worked under the name of the Ayrshire Bauxitic Clay, or A.B.C.

COAL MEASURES (WESTPHALIAN)

The Coal Measures are divided into various groups by their plants and their freshwater lamellibranchs, or mussels (Fig. 306). They are also divided for local convenience according to productivity. The main coal seams can often be traced over large areas, and thus serve as useful stratigraphical indices. They are recognised, partly by their individual character,

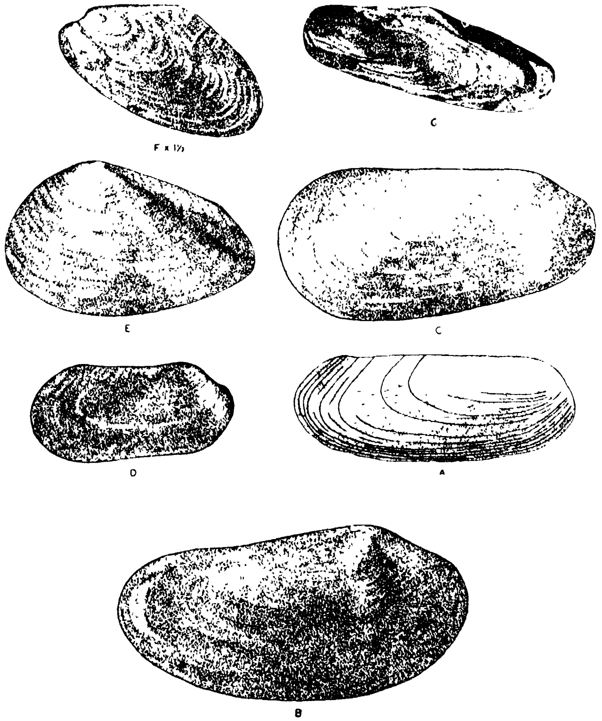

FIG. 306. Coal Measures freshwater mussels. (After Geol. Surv.)

A, *Anthracomya lenisulcata* Trueman, ×1 ; B, *Carbonicola ovalis* (Martin), ×1 ; C, *Anthracomya modiolaris* (J. de C. Sowerby), ×1 ; D, *Anthracomya pulchra* Hind, ×1 ; E. *Carbonicola similis* (Brown), ×1 ; F, *Anthracomya phillipsi* (Williamson), ×1⅓ ; G, *Anthraconauta tenuis* Davies and Trueman, ×1. (After Geol. Surv.)

and partly by their position in regard to other beds, including neighbouring coal seams. The value of coal and the fact that it is widely mined far from any exposure have led to a quite exceptional accumulation of precise geological knowledge. Where, as is fairly common, a coal is succeeded upwards by a shell bed, whether of freshwater origin or marine, the nature of the shells may help materially in identification of the underlying seam. Of late years further guidance has been obtained through statistical study of plant spores that can be separated by chemical treatment from the coal substance (*cf.* Fig. 256).

The deltaic conditions of the Millstone Grit continued into Coal Measure times, but north of the Hercynian Geosyncline they provided many more opportunities for growth of marshy forests that have given rise to valuable coal seams. Flooding with fresh water was responsible at times for extensive beds of freshwater mussels. Marine incursions occasionally brought goniatites or brachiopods. Marine bands are commoner in Wales and England, as far north as the Lancashire Trough, than in Scotland. One widespread marine intercalation, which in Scotland is taken as the somewhat arbitrary dividing line between Productive Coal Measures below and Barren Red Coal Measures above, carries goniatites even in the northern kingdom.

There is a general tendency for productive coal measures to be followed upwards by barren red coal measures. These are devoid of valuable coal seams and are further characterized by red sandstones, variegated marls, and occasional thin beds of *Spirorbis* limestone (*cf.* Fig. 155). It appears probable that the barren measures owe their colour (where it is original) to conditions of deposit that had begun to approximate to those of the succeeding Permian. In various English districts important angular unconformities occur within the upper part of the Coal Measures.

The barren red conditions set in rather earlier in the north than in the south. Thus the time-equivalents of the Barren Red Coal Measures of Scotland carry valuable coal seams in South Wales and Somerset.

LAND AND FRESHWATER LIFE.—The Coal Measure flora consists mainly of:

(1) Plants superficially like tree-ferns, such as *Neuropteris*, *Alethopteris*, *Sphenopteris* (Fig. 265). Many have been proved to be seed-bearing, instead of spore-bearing, and so are not true ferns.

(2) Club-moss trees, such as *Lepidodendron* and *Sigillaria* (*cf.* Figs. 255, 257).

(3) Horse-tail trees, such as *Calamites* (Figs. 259–261).

In the fauna freshwater mussels, such as *Carbonicola* (Fig. 306B), are very abundant. Fish and amphibia are important. Insects are well known.

COMPARISONS ABROAD.—While deltaic conditions reigned in Britain during Coal Measure times, open sea occupied much of Russia. A characteristic product is a marine limestone crowded with foraminifera called *Fusulina* (Fig. 117B). Similar limestone is found in China, Spitzbergen and in some of the United States, as Kansas.

Let us now turn our attention to a hypothetical supercontinent that has been called Gondwanaland, after the Gondwana district of central India. Gondwanaland includes peninsular India, most of Africa, South America, Australia and Antarctica. It is treated as a unit because its constituent parts show many extraordinary similarities of geological history. Moreover, from Upper Carboniferous to Triassic times inclusive, the life-history of Gondwanaland was very different from that of the rest of the world in Asia, Europe and North America. Both these features are well displayed in Upper Carboniferous times, when extensive land-glaciation occurred throughout Gondwanaland. It is astounding to learn of ice-sheets in India, South Africa and Brazil contemporaneous with forests of tropical type in Britain. It almost unanswerably suggests that the position of the earth's crust, with reference to the poles and equator, has changed during geological time. As, however, the glaciated localities extend somewhat beyond the limits of a single hemisphere, it would appear that the earth's crust has not migrated as a whole, but that in late Carboniferous times Gondwanaland was a fairly compact unit clustered about the South Pole, and that its constituent parts have since drifted asunder into their present positions (Fig. 307).

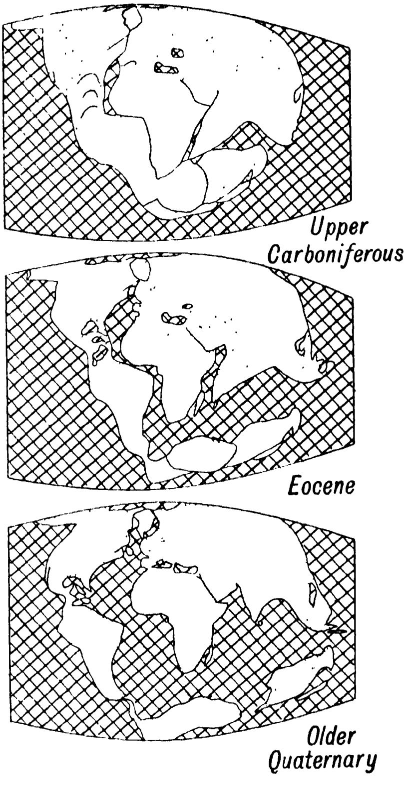

FIG. 307. Reconstructions of the world at three periods to illustrate Wegener's theory of continental drift. The dotted areas are those regions which were covered by shallow seas. (After Wegener.)

Gondwanaland had a very remarkable flora after its glaciation, that is, for the most part, in Permian times. The flora is as widespread as Gondwanaland itself, and yet is quite distinct from the contemporaneous floras of the northern hemisphere. Its commonest genus is *Glossopteris* (Fig. 266).

All geologists are agreed as to the reality of the resemblances which unite Gondwanaland, but many ridicule the idea that its constituent parts have drifted apart. They postulate former land-bridges, as they are called, across the intervening oceans, and suppose that these bridges have foundered.

ECONOMICS OF THE CARBONIFEROUS SYSTEM

The Carboniferous System has been very largely responsible for our present-day civilization. In burning coal, we are recovering, as it were, the sunshine of the Carboniferous period. The main economic products of the system are :

Coal of all qualities, or ranks, to use a modern term, leading up to anthracite.
Cannel or gas coal.
Oil shale in Scotland.
Clayband and blackband ironstone.
Limestone.
Fireclay, ganister, and in Scotland the Ayrshire Bauxitic Clay.
Sandstone.
Lavas and intrusions used for road metal.

CHAPTER LXVIII

PERMIAN

THE Permian is called after the province of Perm in Russia. It is placed at the end of the Palaeozoic. Trilobites continue into it within a Mediterranean belt including the East Indies, Sicily and Texas ; but then die out. *Productus* also continues into the Permian, there to perish. Amphibians are important, and so are reptiles.

Though grouped on palaeontological grounds with the Palaeozoic, the Permian is much like the succeeding Trias in the character of its rocks, as developed in Britain and neighbouring parts of Europe. Both systems contain a considerable proportion of red sandstone, and so are often classed together as the New Red Sandstone, new, that is, with respect to the Carboniferous, just as the Old Red Sandstone is old with respect to the same datum. (It is a curious historical fact that the term Old Red Sandstone originated with a different significance from that which it at present conveys.)

During Carboniferous times mountain ridges had been growing in places within the Hercynian Geosyncline. At the close of Carboniferous times the maximum folding of the Hercynian Chain occurred, and the Hercynian Geosyncline was replaced by a folded mountain chain.

It is a case of History repeating itself. At the close of Silurian times the Caledonian Geosyncline had been raised by folding into the Caledonian Chain, much of the neighbouring platforms had been elevated along with it, and, within and without the chain, Old Red Sandstone had been deposited. Now, at the close of Carboniferous times, not only was the Hercynian Geosyncline folded into the Hercynian Chain, but much of the neighbouring platforms was uplifted too ; and, within and without the chain, New Red Sandstone was deposited.

Another analogy may be noted. The Caledonian Chain was early pierced by great granite intrusions of Old Red Sandstone age in Scotland, Ireland and the North of England. So too the Hercynian Chain was early pierced by great granite intrusions of New Red Sandstone (Permian) age in Cornwall, Devon, and many Continental localities. In an economic sense there is a great difference, for, whereas the Caledonian granites were barren of mineral wealth, the vapours liberated during the consolidation of the

Hercynian granites were responsible for the world-famous tin and copper veins of Cornwall, Devon and the Hartz.

The Hercynian Chain has its frontal thrusts comparable with those of the Caledonian Chain. They are known in Somerset, but better still in Belgium, where coal in Coal Measures has been worked for miles covered by overthrust Carboniferous Limestone.

While, at the close of Carboniferous times, strong folding and thrusting were mainly confined to the course of the Hercynian Geosyncline, gentle folding and strong normal faulting affected the relatively stable platform to the north, including most of British Isles. To this gentle folding is due the bending of the Coal Measures into a series of basins separated by anticlines.

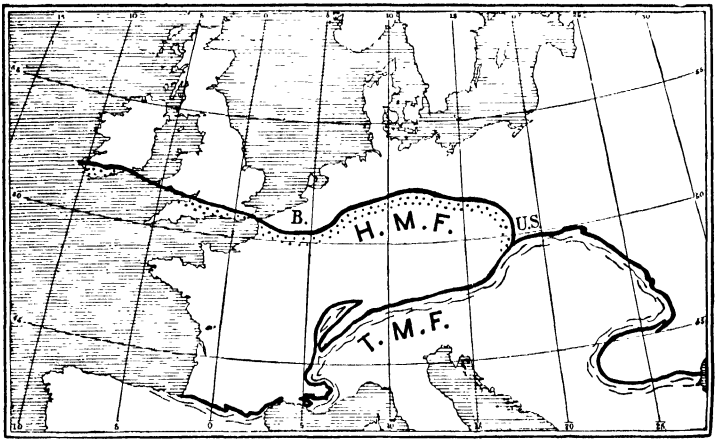

FIG. 308. H.M.F., Hercynian Mountain Front; T.M.F., Tertiary Mountain Front; B., Belgium; U.S. Upper Silesia. (Adapted from E. Suess.)

We need only mention the Lanarkshire and Ayrshire basins in Scotland, and farther south those of Northumberland, Yorkshire, Lancashire and South Wales, the last-named bordering the great Hercynian Chain. That much of this folding was accomplished before the Permian of North-East England was deposited is shown from the unconformity (clearly visible on any geological map of England), which carries the Permian across the outcrops of the Northumberland and Yorkshire coal-basins and the intervening anticline.

The British Permian largely originated as outwash scree and sand laid down on an uneven desert floor. The desert conditions are shown by round grains, dreikanters and dune bedding. In North-East England there was, however, during part of Permian times, an extension of a semi-enclosed sea, which also covered much of Germany. Its deposits are mainly marine limestones; but the desert conditions of its surroundings are shown by accompanying gypsum, anhydrite and salt. The sea for a short time reached across or around the Pennines, but did not penetrate into Devon or Scotland.

NORTH-EAST ENGLAND.—The development in North-East England is very similar to that of Germany, the type area for western Europe. The succession broadly is :

Magnesian Limestone
Marl Slate
Yellow Sands

YELLOW SANDS.—This basal division rests unconformably on various members of the Carboniferous. Its grains show wind-rounding, and it has pronounced current bedding, interpreted as dune bedding. The deposit seems to be a desert sand.

MARL SLATE.—The name slate is misleading geologically, for the deposit is merely a hard brown shale with occasional thin limestone bands. It has yielded fish and land plants that allow of correlation with Germany.

MAGNESIAN LIMESTONE.—This is the biggest and most important division. It is a limestone with varying amounts of calcite and dolomite ; some parts are almost pure limestone, and others dolomite. It is probable that the dolomite was in part precipitated as such on the sea bottom, while in part it certainly represents a reaction between original limestone and concentrated magnesian solutions. Anhydrite, gypsum and local salt deposits are found in connection with the Magnesian Limestone. Amazing concretionary and brecciated structures occur in places, the latter probably resulting from abstraction of soluble salts.

There is no doubt that the Magnesian Limestone formed in a land-locked branch of the sea subject to evaporation. Some beds contain shells such as *Productus horridus* (Fig. 309), while a richly fossiliferous reef crowded with the bryozoan *Fenestella* (*cf*. Fig. 168) has been traced for several miles.

In the similar German succession the Magnesian Limestone has a very rich development of salt deposits, including the potassium salts of Stassfurt.

FIG. 309. *Productus horridus* Sowerby, × ½. (After Zittel)

NORTH-WEST ENGLAND.—The Permian west of the Pennines is comparable with that of North-East England, but is much less marine. It commences in the Penrith district with a great red desert sandstone, full of beautifully wind-rounded grains. Where this sandstone approaches old cliffs of the period it interstratifies with consolidated scree-breccias, largely made of Carboniferous Limestone fragments and called brockram. According to Kendall, certain brockrams in the Vale of Eden, alongside of the Pennines, furnish a record of Permian fault-movement. The local Permian includes two thick bands of brockram, a lower and an upper. It lies at the foot of a fault-scarp, the bottom part of which is now composed of pre-

Carboniferous rocks, and the top part of Carboniferous rocks. Movement along the fault had not proceeded far enough to expose the pre-Carboniferous rocks in lower brockram times, for the lower brockram consists wholly of Carboniferous debris. On the other hand movement had exposed the pre-Carboniferous rocks by upper brockram times, since the upper brockram includes many pre-Carboniferous fragments.

In the light of the above interpretation, which, however, has been questioned, we see that the Pennines were a feature of the Permian landscape. They were uplifts due mainly to faulting, and did not resemble the Hercynian folded mountains farther south.

The Magnesian Limestone sea that entered North-East England from Germany has only left occasional traces of its presence west of the Pennines. Fossiliferous Magnesian Limestone furnishes small outcrops near Whitehaven, Belfast and other localities.

CORNWALL AND DEVON.—The Permian has an outcrop of entirely continental facies in Devonshire. Red sandstones, breccias and conglomerates rest unconformably on the folded and denuded Carboniferous and Devonian of the Hercynian Chain. There are also contemporaneous volcanic rocks. Much more important are the great granites of Dartmoor, Land's End, etc., that pierce the Hercynian folds. These, with associated dykes and mineral veins, must be placed as of early Permian date. The dykes furnish pebbles to the Devonshire conglomerates of the same general period.

SCOTLAND.—What appears to be the Penrith Sandstone outcrops at Dumfries and Thornhill in the Southern Uplands, and at Mauchline in Ayrshire (Fig. 310) and Corrie in Arran (Fig. 4). It has the same red colour and the same wind-rounded grains. At Thornhill and Mauchline the Permian Sandstone includes a basal series of basalt lavas. In them Dr. Tyrrell detected the rather uncommon mineral nepheline. This was the first find of nepheline in a British lava, although its occurrence had previously been noted in a fair number of intrusions.

The Ayrshire volcanic field has many sills and necks. Faulting took place at about the same time as their intrusion, for some of the earlier sills are cut by faults, which in turn are cut by later sills. *Mutatis mutandis*, one is reminded of the time relations of the brockrams to the Pennine fault in the Vale of Eden. The Permian ash necks of Ayrshire are marked by little hills at the surface, while underground they often interrupt the working of coal seams.

Very beautiful exposures of similar necks are met with along the coast of East Fife. They are interpreted as of Permian date because their material is like that of the Permian necks of Ayrshire, and also because they cut through somewhat strongly folded Carboniferous, and seem later than the folding.

The Great Whin Sill of the North of England, and its equivalents in

Scotland, are also early Permian. The sill cuts the Carboniferous, is earlier than some faults and later than others, and has yielded a very few pebbles to the Vale of Eden brockram. It is composed of a special type of dolerite called quartz-dolerite, and is accompanied by an important set of big east and west quartz-dolerite dykes. One of these, traversing the Coal Measures of Durham, is truncated at the base of the unconformable Permian sediments.

New Red Sandstone outcrops occur near Elgin in the Moray Firth district. They have yielded two reptilian faunas, one of which is probably Permian, and the other certainly Trias. The recognition of the New Red Sandstone exposures was a distinct triumph for a medical student, whose name is now known to all, for it is Huxley. The story is as follows :

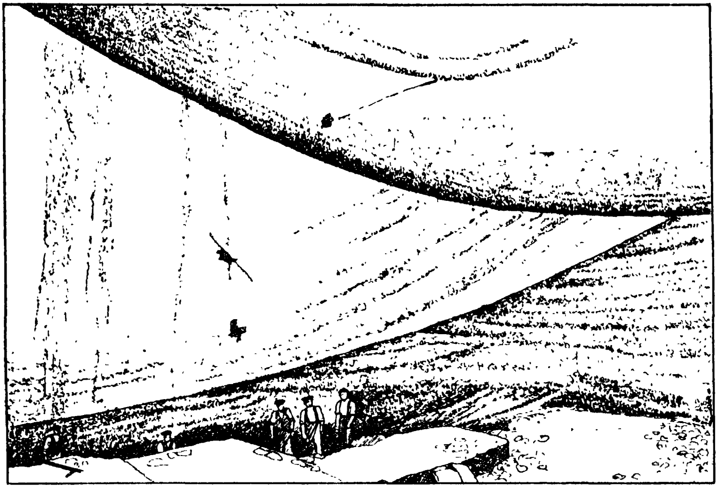

FIG. 310. Large-scale current bedding of desert origin in Permian sandstone, Mauchline, Ayrshire.
Note trains from springs on left. (Geol. Surv. photo.)

The New Red Sandstone of Elgin rests flatly on flat Upper Old Red Sandstone which contains the characteristic fish *Holoptychius.* To begin with, no one doubted that there was just one formation, namely Upper Old Red Sandstone. A bone found in the New Red Sandstone was sent to the great Swiss expert Agassiz, and came back duly named and described as belonging to a fish. However, young Huxley saw the bone, and claiming it for a reptile compared it with reptilian bones of the New Red Sandstone of England. He was right : confirmatory fossils have been discovered, and the top part of the Elgin deposit has been transferred by common consent to the New Red Sandstone—it is separated from the Upper Old Red Sandstone by an unconformity, which without the aid of Palaeontology, is undetectable.

The portion of the Elgin deposit, which is supposed to be Permian, rather than Trias, has yielded particularly remarkable reptiles closely related to contemporaneous forms in South Africa, that is in Gondwanaland. Many of these strange reptiles in the Elgin sandstone have been preserved as hollow moulds. Into one of these, gutta-percha is poured, allowed to set, and then pulled out, a fearsome-looking beast, complete with horns (Figs. 217, 220).

TETHYS.—For a thoroughly marine development of the Permian we have to go to the region stretching from Sicily east to the Himalayas. Here we find a geosynclinal sea separating the main Eurasian lands on the north from Gondwanaland on the south. This Mediterranean sea, of which the present Mediterranean is a survival, has been called the Tethys. It was analogous to the Caledonian and Hercynian geosynclines of earlier days. It was also the birthplace in Permian times of the post-goniatite types of ammonites, which did not reach Britain until the Jurassic.

GONDWANALAND.—In Gondwanaland the glaciation of Late Carboniferous times was passing, or had passed, at the start of the Permian. The latter is represented by continental deposits with valuable coal seams. The *Glossopteris* flora was at its height, extending on into the Trias. Reptiles began to be abundant and in some cases showed mammalian affinities.

ECONOMICS.—The Magnesian Limestone is an important source of lime and building stone. Famous buildings made of it include York Cathedral (not Durham as is sometimes stated) and the Houses of Parliament. In the latter it has not stood well against the London atmosphere, and has recently been replaced in large measure by Jurassic oolite.

Sandstone furnishes building stone as at Penrith and Mauchline.

Lavas and intrusions provide road metal and setts; and the granites of Cornwall and Devon are much used for ornamental work.

Salt is worked near Middlesborough.

Tin and copper veins have long been worked in Cornwall and Devon. Other metalliferous veins, as in the North of England and in the Leadhills of Scotland, may be of this date.

As igneous rocks furnish the best road metal, and as there was a long pause in British igneous activity after the Permian, we may add a few words about road metal in general. Hardness and durability make igneous rocks specially useful for road metal. Basic types of medium texture give the best results. Granite binds badly with tar. Among sediments limestone binds well, even without tar, but untarred is too soft to withstand heavy traffic. Quartzite and flint are much used, but are brittle and bind badly without tar. Ferruginous laterite is useful in tropical countries.

CHAPTER LXIX

TRIAS

MESOZOIC LIFE COMPARED WITH PALAEOZOIC.—On passing from Permian to Trias let us note some of the distinguishing features of Mesozoic life as compared with that of the Palaeozoic era. The contrast is much emphasized in our country because we have very few fossils in the Permian and Triassic formations. In a complete record the change would be gradual.

Trilobites, eurypterids, blastoids, cystoids and graptolites are extinct.

Rugose corals are replaced by hexacoralla with six-fold symmetry.

Brachiopods are greatly reduced in importance, except for two super-families, the Rhynchonellacea and Terebratulacea.

Lamellibranchs and gastropods are greatly increased.

Ammonites, which flourished in the Tethys in the Permian and Trias, are very abundant in Britain in the Jurassic and Cretaceous.

Belemnites also arrive (Fig. 182).

Reptiles become dominant on land and in sea and air. They started in the late Carboniferous.

Mammals and birds begin.

Seed-ferns and giant club-mosses are replaced early in the Mesozoic by conifers and trees very like cycads (Chapter LVII). Later these are joined by the true flowering plants, the angiosperms.

STRATIGRAPHY.—The Trias, the first of the Mesozoic systems, forms the upper part of New Red Sandstone. It receives its name from its three-fold division in Germany, marked by an important middle group of marine limestones. The Trias of Britain, if we exclude the Rhaetic at its top, is completely continental. For open-sea Trias we must go to the Mediterranean-Himalayan belt, that is to the Tethys, where ammonites abounded. Some were of the ceratitic type, peculiar to the Trias (Fig. 181G); but the majority had more complex sutures (Fig. 183B).

In the greater part of Europe the Trias formed as a continental deposit, varied by incursions of the sea. The German development is :

UPPER TRIAS.—RHAETIC with *Pteria contorta* (included by the Germans as Upper Keuper, but by the French as Lower Jurassic). KEUPER red marls with gypsum and salt.

Middle Trias.—Muschelkalk marine limestones and dolomites with lamellibranchs, such as *Gervillia* (*cf.* Fig. 187H), and six-symmetry corals, as *Montlivaltia*.

Lower Trias.—Bunter red and variegated sandstones with gypsum and salt.

These names are derived as follows: Bunter from the German for variegated. Muschelkalk from the German for mussel-limestone; Keuper from a German mining term; Rhaetic from the Rhaetic Alps, east of the Rhine.

In Britain the conditions were more continental than in Germany, and nothing like the marine Muschelkalk is known. The succession is:

Rhaetic, with *Pteria contorta* shale and bone bed almost at the base.
Keuper, red and green marls and, in Cheshire, salt and gypsum.
Bunter, red and variegated sandstones and conglomerates.

The outcrop of the Trias, starting near Exeter in the south, expands on reaching the English Midlands, and bifurcates to send one branch northwest through Cheshire to continue beneath much of the Irish Sea, and another northwards through Yorkshire to reach the North Sea coast at Middlesborough (*cf.* Fig. 278). The Irish Sea branch comes ashore in the Isle of Man and at Carlisle. Remains of it are found farther north in Antrim, Arran, Mull and Skye. The North Sea branch is seen in Scotland at Elgin and Golspie. The northward continuation of the two branches of the Trias outcrop of the English Midlands brings home the fact that Scotland may be viewed as the northward continuation of the Pennines of England, or *vice versa*.

It used to be thought that a very important unconformity separated the Permian of England from the Trias. Now, however, it is generally agreed that there is lithological transition from the one system to the other. Naturally under these circumstances it is difficult to decide where the one ends and the other begins, especially as fossils are generally absent from the debatable part of the succession. One thing is certain, the Trias is more widespread than the Permian, and often rests directly on Carboniferous and pre-Carboniferous rocks.

The conglomerates, or pebble beds, of the English Bunter are interesting, because they sometimes contain, in addition to local Palaeozoic material, pebbles of a well-known French (and Cornish) Ordovician quartzite, recognizable by its fossils. These quartzite pebbles are found in Devonshire, and extend into the Midlands. They suggest that intermittent rivers were flowing from the Hercynian mountains of France and discharging their load far over the desert floor of Britain.

The Keuper Marls, with their deposits of salt and gypsum in Cheshire, indicate the presence of an inland lake or lagoon, subject to desiccation under desert conditions.

The Rhaetic is marine, and records a marine transgression into the inland lake. It has a continuous outcrop from Devonshire to Yorkshire. The characteristic fossil *Pteria contorta* is a marine lamellibranch. The bone bed abounds in remains of reptiles and fishes, and is particularly famous for having yielded the tooth of the first known British mammal. This early mammal is classed among the primitive allies of the pouched group of marsupials, which latter have managed to escape extinction to this day in Australia and also, in the case of the opossum, in America.

Mammals are the descendants of reptiles. In their earliest forms they laid eggs. The duckbilled platypus and the echidna of Australia and New Guinea are surviving examples. Then they gave up laying eggs, and tucked their new-born offspring into pouches. This is the marsupial type, now almost restricted to Australasia. Little understood, but possibly related, early types were represented in the northern continents in Mesozoic times. The modern types of mammal did not evolve till Tertiary times. They originated somewhere in Asia, Africa, Europe or America. By that time Australasia was cut off by the sea, and so has served as an asylum for the older kinds.

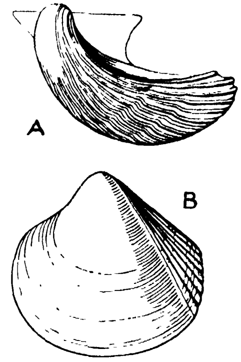

FIG. 311. Rhaetic marine lamellibranchs. (After Geol. Surv.)

A. *Pteria* [*Avicula*] *contorta* (Portlock), × 1; B. *Protocardia rhaetica* (Mérian), × 1.

In Scotland, much of Arran consists of Trias. In the absence of fossils it is impossible to draw a convincing line between it and the Permian. However, on lithological grounds it is clear that Keuper Marls are well represented. Rhaetic has only been preserved in the form of a great fallen block which slid down the throat of a Tertiary volcano. It contains the zone fossil *Pteria contorta*.

At Elgin the greater part of the reptiliferous sandstones are certainly Triassic. They contain crocodile-like Pseudosuchia proper to the period.

In the Hebrides, for instance in Mull and Skye, Mesozoic rocks often shelter below the lavas of Tertiary volcanoes. These Mesozoic rocks start with grey sandstone and conglomerate with cornstone concretions, undoubtedly Triassic though unfossiliferous. At one locality in Mull the cornstone-bearing rocks are overlain by shaly sandstone of Rhaetic age with *Pteria contorta*; elsewhere they are followed by Lias forming the base of the Jurassic.

ECONOMICS.—Among the economic products of the Trias we may note:

Salt, locally mined, but usually brought to the surface as brine.

Gypsum and alabaster.

Marl, for brick-making.

The last commonly-used building sandstones.

Low drift-covered country in Cheshire, admirable for dairying.

Water of the English Midlands, largely got from wells and bores in Triassic sandstones. Hence a particular sandstone division of the Keuper is known as the Waterstones.

CHAPTER LXX

JURASSIC

THE Jurassic System is called after the Jura Mountains, north of the Swiss Plain. These mountains are mostly made of Jurassic limestones, strongly folded.

The system is divided into two main divisions :

Oolites
Lias

The Lias in Britain consists chiefly of interbedded shales and thin limestones. The name is a local quarryman's word and is derived by some authorities from layers, and by others from the Celtic *leac*, a flat stone.

The Oolites in England carry prominent oolitic limestones interbedded among thick clay formations. In Scotland the Oolite division does not have this oolitic facies.

Attention has already been drawn to the distribution of the Trias on the map of the British Isles. That of the Jurassic follows the same plan, and is very conspicuous in the colour pattern adopted by the Geological Survey. The Lias is shown in deep brown, the Oolites in bright yellow. The main outcrop of the Jurassic starts from the English Channel at Lyme Regis in Dorset, and reaches the North Sea between Saltburn and Scarborough in Yorkshire. This outcrop, combined with that of the associated Trias, divides Britain geologically into the old and the new (*cf.* Fig. 278). All the Palaeozoic and older outcrops lie west of this line. Many of these old rocks have been involved in either the Caledonian or Hercynian mountain-making movements ; many of them are igneous ; one other, though unfolded and sedimentary, is a compact limestone, the Carboniferous Limestone, often called the Mountain Limestone. To these old outcrops we turn, whether in Devon, Wales, the Lakes, the Pennines or Scotland, when in search of fine bold scenery. To the east the rocks are Mesozoic or Tertiary, and the scenery, though beautiful, is relatively mild. The division into old and new continues into economics. All the exposed coalfields, such as have been worked from the early days of the industrial revolution, lie west of the Mesozoic outcrop. The same holds good in regard to the metalliferous veins (but not the bedded ironstones). In a sense this distinction is passing, for coalfields continue locally under the later rocks to the east. Such coalfields are called concealed coalfields. The concealed eastward continuation of the Yorkshire coalfield is at present being actively exploited. In fact, it is one of the most important coal districts in Britain. A concealed coalfield has also been located in Kent. It is an expensive coalfield to work, but its southern situation is a valuable asset. Concealed coalfields are discovered and explored by boring, and fossils have proved invaluable in the interpretation of the cores brought up from the bore holes.

The Geological Survey map of the British Isles shows two points of special interest in relation to the main Jurassic outcrop. First let us note a westward prolongation past Cardiff. This has guided to a considerable extent the erosion of the Bristol Channel. Next let us look north of the Humber. Here we see unconformable Cretaceous rocks passing across an anticline, along which erosion has almost completely removed the Jurassic previous to the deposition of the Cretaceous. Some Lias continues across the anticline, although too thin to show on the small-scale of the map. This anticline is known as the Market Weighton uplift, and has been carefully studied. The relations of the several Jurassic series to one another show repeated uplifts and unconformities at the axis. The anticline was forming on the sea bottom throughout Jurassic times. In post-Cretaceous times it seems to have been flattened out by a gentle syncline of Tertiary date.

The main Jurassic outcrop after reaching the Yorkshire coast does not stop, but merely passes under the water. We know already how the associated Trias reappears near Elgin on the Moray Firth and at Golspie on the east coast of Sutherland. The Jurassic outcrop follows and is well seen at Brora and Helmsdale in Sutherland, where its inland boundary is a great north-east fault to which we shall return later. One is safe in regarding much of the bed of the North Sea as eroded in the soft Mesozoic and Tertiary rocks that make south-east England.

Let us recall how the Triassic outcrop divides in the English Midlands and sends a branch by Cheshire to floor much of the Irish Sea, and how this branch can be traced discontinuously by way of Antrim and Arran to the Inner Hebrides (*cf.* Fig. 278). The Jurassic follows the Trias, though with greater interruptions. Ordinary outliers of Lias are found in Shropshire and near Carlisle. Others are preserved in Antrim under the Tertiary lavas. Two patches have escaped destruction in Arran, by falling down, one into a volcanic neck, the other into a volcanic fissure. Farther north, in Mull, Skye and other islands, Oolites, as well as Lias, are sheltered beneath Tertiary lavas in regions of subsidence.

No one can think of the Jurassic without remembering that it was in this system that William Smith, the Father of English Geology, laid the foundations of stratigraphy (Fig. 312). A civil engineer and mineral surveyor, he was concerned with such matters as canals and quarries. He lived in the Bath district, and covered a wide area in his professional travels. The English Jurassic afforded him an ideal opportunity. Its successive formations have distinctive lithology, and they teem with fossils that change rapidly from horizon to horizon. The clay formations make long hollows along their outcrops. The more resistant oolites rise above them in steep escarpments. A gentle dip to the east is almost everywhere apparent. There is very little faulting. The clays are laid bare in pits, and the oolites in quarries. Smith taught the world that 'the same strata are found always in the same order of superposition and contain the same peculiar fossils'.

FIG. 312. William Smith.

The main series in the English Jurassic are :

Upper Oolites	Purbeck Portland Sand and Oolite Kimmeridge Clay
Middle Oolites	Corallian Oxford Clay
Lower Oolites	Great Oolite, etc. Inferior Oolite
Lias	Upper Middle Lower

Smith not only propounded principles, but made maps. His geological map of England and Wales is an amazing monument to his energy and skill. A copy is hung on the staircase of the Geological Society of London.

Ever since Smith's day palaeontologists have been busy refining upon his work, and have found in the Jurassic one of their main sources of inspiration. There are now about 110 successive zones recognised in the Jurassic, each distinguished by some particular ammonite. The ammonites of the Mesozoic, like the graptolites of the Early Palaeozoic, make ideal zonal fossils, for again and again we find a species which has a wide geographical range and yet is restricted vertically to a small thickness of beds. It is quite common in the Lias, for instance, to find ammonite zones only ten feet thick ; in fact, they are often much thinner.

There is one point that it is necessary to understand. As a rule the ammonites of successive zones are not in lineal descent. It is not like a succession of kings, where son follows father ; but much more like a succession of presidents, where selection picks the successful candidate from a host of possibles. Thus one zone-fossil after another comes into prominence and passes out of sight. Probably we shall never know exactly what combination of qualities and chances gave each zone-species, or group of associated zone-species, its short-lived opportunity to multiply and stamp the rocks of its period with the impress of its personality.

And now briefly for the story which these rocks tell.

The marine transgression of the Rhaetic marks the real introduction of Jurassic conditions into Britain—except that it brought no ammonites, in this resembling the Muschelkalk transgression of Germany.

The history of most of the Jurassic is one of widespread shallow marine submergence, locally and temporarily giving place to deltaic or estuarine conditions. One part at least of our islands remained uncovered. Deep borings show that a ridge of Palaeozoic rocks kept its head above water in East Anglia, continuing a short distance south of the Thames. Thus north of London the Trias of the Midlands does not extend underground much beyond the Cretaceous escarpment. East of this we find Lias, Oolites, and finally Cretaceous, resting directly on the Palaeozoic foundation.

Four Scottish localities furnish evidence of differential movements affecting the sea bottom in Kimmeridge times. It was at this date that the boundary fault at Brora and Helmsdale was formed, with a development of boulder beds for miles along its course (*see* Chapter XLII).

These Scottish disturbances were followed by withdrawal of the sea to the South of England in Portland times. Finally, in Purbeck times, all that remained was an estuary in the south-east of England—which escaped important earth movement until after the deposition of the Wealden of Lower Cretaceous date.

And now for a few words about each main division.

The LIAS consists very generally of marine shales and limestones. Besides ammonites we may mention *Gryphaea arcuata* as a very characteristic oyster of the time. The Lias at various levels in different localities contains valuable ironstones, for instance in Lincolnshire and Yorkshire and in Raasay in the Hebrides. These ironstones used to be interpreted as oolitic limestones replaced by iron compounds, but are now recognised as originally composed of chamosite and siderite.

The LOWER OOLITES are wholly marine in the South of England and contain the famous Bath Oolite. Northwards from the English Midlands, through Yorkshire into Scotland, they are largely estuarine. At Brora a coal seam, belonging to this estuarine facies, is worked at the top of the Lower Oolite to bake bricks made from overlying marine Oxford Clay. Ironstone occurs in Northamptonshire.

The MIDDLE OOLITES are marine throughout their extent. The Oxford Clay has a very widespread clay facies ; and in England the Corallian often has a coral reef and oolitic facies.

The Kimmeridge Clay of the UPPER OOLITES is another widespread marine clay both in England and Scotland, for instance at Kimmeridge in Dorset and at Helmsdale in Sutherland. At the latter locality it carries many intercalated boulder beds, to which attention has already been directed (Figs. 112, 113).

The Portland is marine and restricted to the South of England, where its most important member is the Portland Oolite.

The Purbeck is mainly fresh-water, and some of its limestones are made of the fresh-water snail, *Viviparus*, etc. It also includes a fossil forest (Fig. 313), and has yielded several bones of very primitive mammals.

FIG. 313. Fossil tree encased in calcareous tufa, Purbeck horizon, Dorset. (G. M. Davies photo.)

LIFE.—The reptiles of the Jurassic were the dominant creatures of the time (Chapter LII) ; many of them were huge land or sea animals, comparable in size with elephants and whales among modern mammals. Some of the smaller types flew about in the air like bats. Most of the orders then living are now extinct. We may mention the land dinosaurs, the sea plesiosaurs and the flying pterosaurs or pterodactyls.

The most interesting fossils ever discovered are, perhaps, two specimens of *Archaeopteryx* (the original of Fig. 314 is sometimes distinguished as *Archaeornis*), missing links between the reptiles and the birds. They were found in a very fine-grained limestone (lithographic stone) at Solenhofen in Germany. This stone formed as an ooze in the lagoon of an atoll of Upper Oolite age, and contains many other wonderfully preserved fossils. *Archaeopteryx* was a bird with feathers, but it still retained the following reptilian characters : a long bony tail, claws to the wing fingers, and teeth.

As already mentioned, a number of bones of very primitive mammals have been found in the Jurassic.

Among plants, ferns and horse-tails are abundant, also the venerable *Ginkgo* (*cf.* Fig. 274), mock cycads, and true conifers, including the type represented to-day by the monkey-puzzle tree. A few problematical flowering plants (perhaps even angiosperms) also occur.

Brachiopods are plentiful, but mostly belong to two clans, the relatives of *Terebratula* (Fig. 315), and *Rhynchonella*.

Lamellibranchs are abundant: *Trigonia, Gryphaea* (Fig. 2), *Lima, Leda, Gervillia* (Fig. 187). It is interesting to note that *Trigonia* (Fig. 315) has long been extinct except in Australian waters, where it has found a sanctuary, just as have marsupials on the neighbouring land.

FIG. 314. *Archaeopteryx siemensi* Dames. Original in Berlin Museum, often called *Archaeornis*. (After Zittel.)

Sea urchins: *Cidaris, Holectypus*.

Corals: *Montlivaltia, Stylina*. The presence of coral reefs at various levels in the English Jurassic confirms the evidence of the oolitic limestones. The seas must have been of tropical warmth.

Belemnites abound.

Ammonites, the main time-keepers of the succession, include *Phylloceras* (Fig. 181H), *Dactylioceras, Hildoceras, Cosmoceras, Amaltheus* (Fig. 315).

ECONOMICS.—The oolitic limestones furnish very valuable freestones. The Bath Oolite and Portland Oolite are particularly well known.

The Purbeck Marble is a dark limestone full of the freshwater snail, *Viviparus*. It had a great vogue for indoor work in cathedrals of the Early English Gothic Style, such as Salisbury.

The Oxford and other clays are much used for bricks.

The Lias limestones and clays are employed for Portland cement. The latter has no connection with Portland Oolite, except that at a distance both look somewhat alike. Portland cement is made by grinding limestone and clay, mixing them as a mud, drying, heating until fusion begins, and regrinding to a powder. When this powder is wet a number of chemical reactions follow that lead to setting.

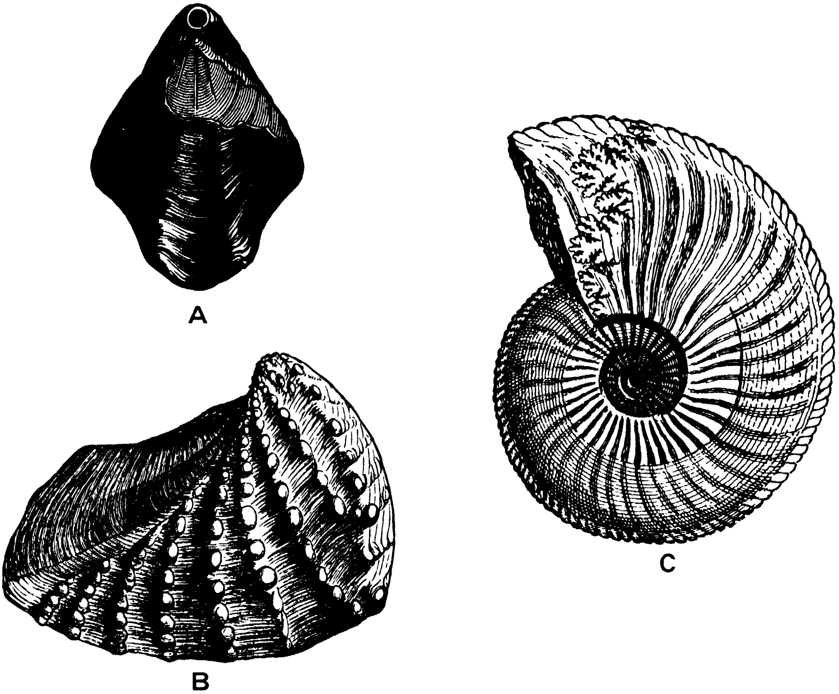

Fig. 315. Jurassic brachiopod, lamellibranch and ammonite. (After Zittel.)
A. *Terebratula phillipsi* Morris, × 1. B. *Trigonia navis* Lamarck, × 1.
C. *Amaltheus margaritatus* Montf.

Attempts have been made to use the Kimmeridge Clay as an oil shale. Up to date they have been unsuccessful.

The ironstones of the Lias and Inferior Oolite are very valuable. They are mainly chamosite-siderite ironstones.

CHAPTER LXXI

CRETACEOUS

The Cretaceous System is called after the Latin *creta*, meaning chalk. In northern Europe, including Britain, it is characterized by a strong development of chalk and glauconitic greensands.

In late Jurassic times the sea had practically retreated out of Britain, only maintaining an estuary in the south-east. This estuary was continued as a lake, or estuary, in earliest Cretaceous times. Meanwhile open sea invaded Norfolk, Lincolnshire and Yorkshire from the east, leaving an exposed ridge at London, a survival of the East Anglian ridge of Jurassic and Triassic times. The further history of the Cretaceous records the submergence of the London ridge, and the discontinuous advance of the sea farther and farther west across the outcrop of pre-Cretaceous rocks. The advance, or transgression, was particularly active at the beginning of Upper Cretaceous times, preceded, in the South-West of England, by an interval of folding, faulting and erosion at the close of the Wealden. This Upper Cretaceous transgression took the sea into Devon, Antrim and the Hebrides. It was also strongly marked outside the British Isles.

The formations recognised in the South-East of England and exposed in the dome of the Weald are :

UPPER CRETACEOUS	Chalk	
	Upper Greensand	
	Gault	
LOWER CRETACEOUS	Lower Greensand	
	Weald Clay	Wealden
	Hastings Sands	

The Weald is an admirable natural geological model showing the influence of rock character upon erosion. The chalk and sands give ridges and escarpments, and the clays give flat belts. The chalk and especially the sands are soft, but they are also permeable, so that they escape a great deal of the stream erosion that washes away the clays.

The HASTINGS SANDS are mainly sand partly consolidated to sandstone, but contain some clay, lignite and clayband ironstone. Lithologically they are reminiscent of the Coal Measures. The fossils are largely land-plants and fresh-water fish, lamellibranchs and gastropods, accompanied by dinosaurs.

The WEALD CLAY is a clay formation, with similar fossils, and includes a pine-raft in one of its Isle of Wight exposures.

These two formations are grouped together as the WEALDEN, and form a natural upward continuation of the estuarine Purbeck of the Jurassic in South-East England. North of the London ridge, in Norfolk, Lincolnshire and Yorkshire, their place is taken by thoroughly marine deposits, including the SPEETON CLAY, which have northern fossils such as occur in parts of Russia. The Speeton Clay rests on eroded Kimmeridgian Clay.

The LOWER GREENSAND, where green, is coloured by grains of the Fe-Al-K-silicate glauconite, but much of the deposit is red coloured by more or less hydrated ferric oxide. The sea by this time had advanced into the south-eastern estuary, and had established a strait by way of Oxford, separating the London ridge and the western land, and connecting the south-eastern and Yorkshire areas. The same type of deposit accumulated in both regions. Owing to the expansion of the sea the Lower Greensand is often the local basal member of the Cretaceous in England.

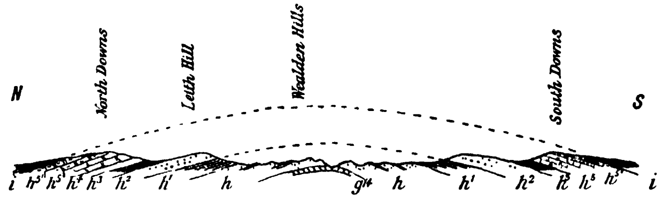

FIG. 316. Diagrammatic section across the Weald. (After Watts.)
g^{14}, Purbeck ; h, Hastings Sands ; h^1, Weald Clay ; h^2, Lower Greensand ; h^3, Gault Clay ; h^5, Chalk ; i, Tertiaries.

The GAULT is a blue or green clay, sometimes called the blue slipper in the South of England, because it causes many landslips of the overlying formations. It is a marine deposit, and varies in character from place to place. In Norfolk it passes into a red-stained chalk, and in the West of England into a greensand. It is very transgressive in the West of England, stepping right across denuded outcrops of Early Cretaceous formations on to Jurassic and Trias.

The UPPER GREENSAND is ill-defined, for there are various local greensand developments, both in the Gault, and in the lowest part of the Chalk (called the Chalk Marl). It is perhaps better to speak of the Upper Greensand as a facies rather than a horizon. The lowest member of the transgressive Upper Cretaceous of Antrim and the Hebrides is Upper Greensand of Chalk Marl age. It rests on many members of the Oolites, often on the Lias, and sometimes even on the Trias.

The CHALK is the most widespread, and generally the biggest, of the Cretaceous formations. In parts of England it is as much as 1000 feet thick, and it extends through northern France and Germany to the Crimea in Russia.

It thins westward in Britain, and suffers partial replacement by both green and white sands, the latter abounding in wind-rounded grains. The Upper Cretaceous succession in Mull is :

	Ft.
Upper Chalk	10
White Sandstone	10
Upper Greensand of Chalk Marl age	10

A similar succession occurs nearby in Morven, where the grains of the white sandstone are particularly well rounded. They seem to have accumulated in the sea ; but they were certainly wind-rounded, and it is thought that they must have been blown into the sea from a neighbouring desert shore. In keeping with this it is found that if we take a specimen of chalk from almost any locality in England or France, and dissolve it in acid, we obtain a small residue that includes wind-rounded grains of quartz.

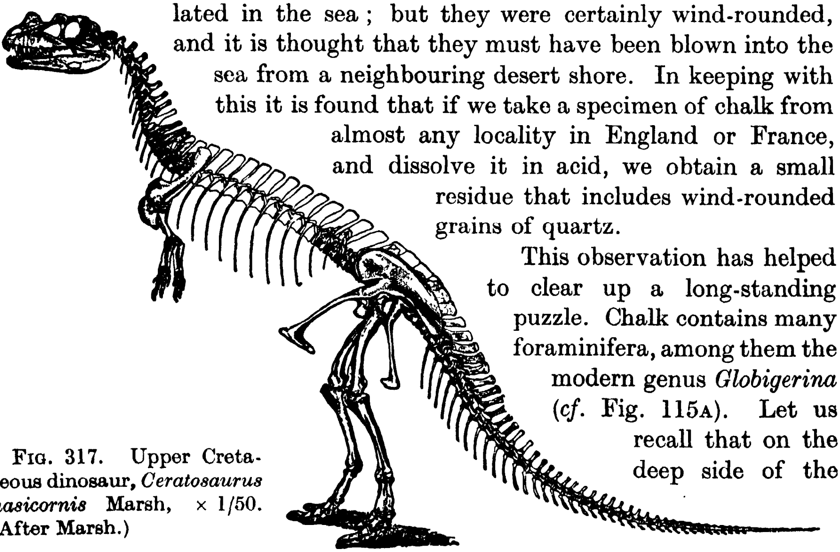

FIG. 317. Upper Cretaceous dinosaur, *Ceratosaurus nasicornis* Marsh, × 1/50. (After Marsh.)

This observation has helped to clear up a long-standing puzzle. Chalk contains many foraminifera, among them the modern genus *Globigerina* (*cf.* Fig. 115A). Let us recall that on the deep side of the Mud Belt on the ocean bottoms of to-day we enter foraminiferal, often called *Globigerina*, ooze. When deep-sea deposits first came to be investigated the close resemblance of Cretaceous chalk to modern *Globigerina* ooze was realized ; and it was suggested that the chalk, like the modern ooze, had accumulated at great depth. Let us clearly understand that the modern *Globigerina* ooze is characteristic of great depths merely because shallower waters are usually within reach of mud from the continents. *Globigerina* is a floating organism during life ; its presence in the chalk does not necessarily indicate a deep bottom. When the creatures that actually lived on the bottom of the Chalk sea, such as the lamellibranchs and sea urchins, were taken into account it was seen that they were of fairly shallow-water types. Accordingly it came to be recognised that the chalk was a shallow-water *Globigerina* ooze. It remained for a time a problem how this shallow-water ooze had escaped contamination with terriginous mud. Probably part of the answer is that the neighbouring continents, to judge from the extent of the Upper Cretaceous transgression, had largely passed into the condition of peneplains. Probably also climate was a very important factor. If, as we have seen, the coasts of the neighbouring continents were deserts, then few or no rivers would reach the coast to discharge their load of mud. All that got into the sea would be the material blown in by the winds.

The Chalk of England is divided into :

Chalk with flints
Chalk with few flints
Chalk without flints
Chalk Marl

The material of the flints seems to have been derived from spicules of siliceous sponges.

The chalk is zoned mainly by the use of echinoids. In the Upper Chalk *Micraster* suddenly appears (Fig. 318). It can scarcely have evolved in the British area, because no creatures like it have been found in the Middle or Lower Chalk. It seems to have evolved somewhere else and then migrated, ready made, to Britain. After its arrival it slowly changed its characters, and it is possible to tell fairly closely from what stratigraphical level in the Chalk any particular specimen has been collected by paying attention to the details of its shape.

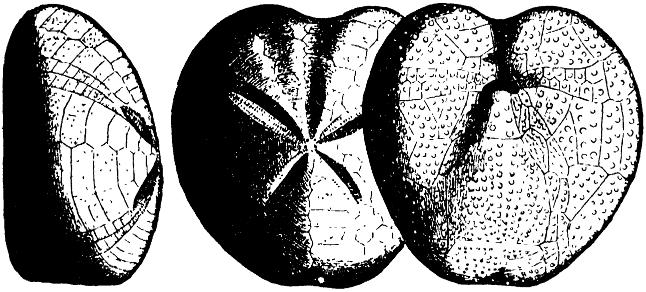

FIG. 318. Upper Cretaceous sea urchin. *Micraster cortestudinarius* Goldf., × ½. (After Zittel.)

A feature of the English Chalk that attracts a good deal of attention is the very occasional occurrence in it of erratic boulders. These have sometimes been ascribed to floating ice, but the general evidence of the life of the time suggests that the Chalk sea was a warm sea, far too warm to carry icebergs. The erratics must have been floated by trees.

South of the Chalk, along the course of the Tethys in the West Indies, the Mediterranean and the Himalayas, there lies a belt of Cretaceous deposits, characterized by lamellibranchs of a very unusual type called rudistid (*Hippurites*, etc., Fig. 319B). They have very unequal valves, are very massive and are something like corals in appearance. They accompany corals, and almost certainly indicate very warm equatorial seas.

LIFE.—One of the main features of the Cretaceous is that true flowering plants, angiosperms, are abundant. Examples occur in Britain as early as the Lower Greensand.

A strong argument for drifting continents is supplied by the rich Cretaceous flora of Greenland, containing some plants, such as the bread fruit, which now only occur in low latitudes.

Foraminifera are important as rock-builders in the Chalk.

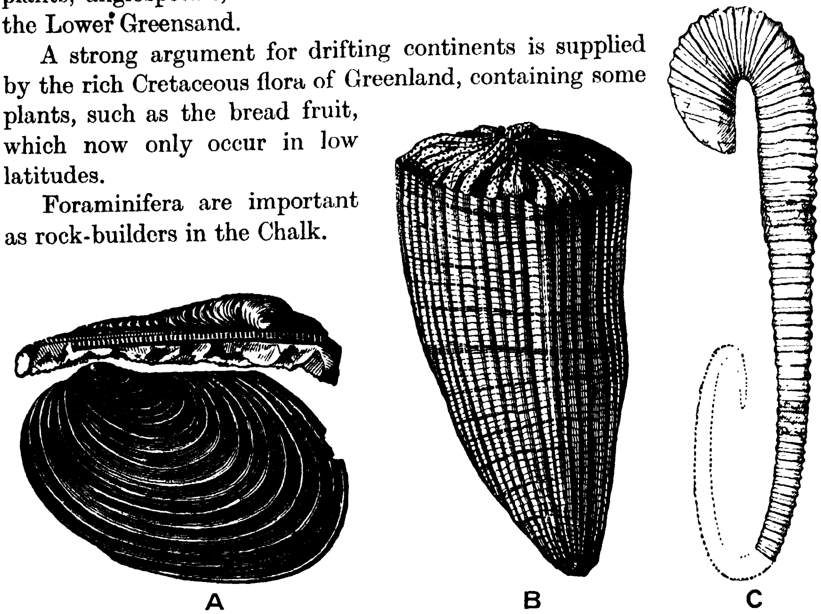

FIG. 319. Upper Cretaceous lamellibranchs and ammonite. (After Zittel.)
A. *Inoceramus crispi* Mant., x ½. B. *Hippurites gasaviensis* Douv., x ½.
C. *Hamites rotundatus* (Sowb.).

Sponges are common (Figs. 121–123).

Echinoids are prominent: *Holaster, Micraster* (Fig. 318), *Cidaris.*

Lamellibranchs thrive as *Spondylus* (*cf.* Fig. 187 D, E), *Inoceramus* (Fig. 319A), *Pecten* and, in the Tethys, *Hippurites* (Fig. 319B).

Brachiopods continue to be represented by the relatives of *Terebratula* and *Rhynchonella.*

Ammonites uncoil and die: *Schloenbachia* (Fig. 181A), *Hamites* (Fig. 319C), *Baculites* (Fig. 181I).

Belemnites abound (*cf.* Fig. 182C).

The bony fish of to-day, called teleosts, and the sharks, are both very common.

Reptiles play the same part as in the Jurassic (Figs. 228, 317).

Some of the birds are still toothed.

Mammals are fairly well known in America. The types represented are still extremely primitive.

ECONOMICS.—The following are characteristic economic products :

Chalk burnt for lime or for Portland Cement (chalk and clay) ; or ground for whiting ; or used for indoor freestone and carving.

Flint for local building stone and road metal.

Gault for bricks.

Lower Greensand, sometimes so ferruginous as to be used as iron-ore, sometimes so purely quartzose as to be used as glass sand.

White-sand of Morven (of Chalk age), suitable for glass sand.

Water from chalk and greensands.

CHAPTER LXXII

TERTIARY

INTRODUCTION.—Kainozoic means the age of recent life. The names Tertiary and Quaternary are employed because the Palaeozoic and Mesozoic are frequently called Primary and Secondary.

A widespread unconformity separates the Tertiary from the Mesozoic, though in the Great Plains of America there is conformity between continental Tertiary and continental Cretaceous. In Britain the unconformity is of the non-angular type called disconformity (Fig. 320). The flints of the Chalk reappear in the Tertiaries as pebbles indicative of erosion.

FIG. 320. Reading Beds resting disconformably on Chalk, which has been bored by marine animals, Harefield, Middlesex. (Geol. Ass., 1914.)

The plant life of Tertiary time records the continued dominance of the angiosperms, started in the Cretaceous. Grass becomes increasingly important, and guides the development of herbivorous mammals.

Ammonites and typical belemnites are extinct.

Lamellibranchs and gastropods and six-symmetry corals continue to flourish.

Brachiopods have fallen very much into the background.

Toothed birds are replaced by living families.

Dinosaurs, great marine reptiles (except turtles), and flying reptiles are all extinct. It is not known what killed them in all parts of the world at approximately the same time. It may have been microbes. It does not seem to have been change of climate for there is no marked change in plant life at the top of the Cretaceous in the full American record. It almost certainly was not mammals. At the beginning of Tertiary times the mammals appear to have been an insignificant group. When they found the world empty they took possession, and developed into the modern families, such as horses and lions for the land, whales and seals for the sea, bats for the air (Chapter LIV). The modern families are not recognisable until the close of the Paleocene, the first of the Tertiary systems. True man waited approximately until the Quaternary; but apes and monkeys were common earlier.

One of the greatest fascinations of the Tertiary is afforded by the genealogies that it furnishes of present-day mammals. We learn how the elephant stock started as an ordinary small pig-like creature. The next stage was the development of long jaws with tusks at the end, with which the animal dug up roots (Fig. 321). The nose was at the end of the jaws as in most animals.

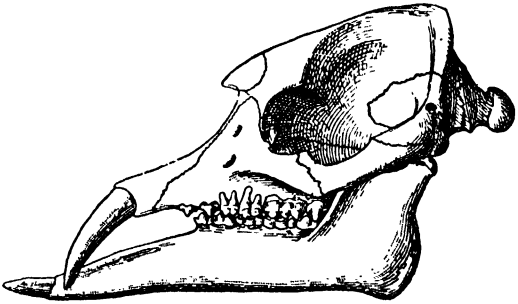

FIG. 321. Oligocene elephant, *Palaeomastodon beadnelli* Andrews, × 1/10. (After Andrews.)

Then for some unknown reason the bones of the face shortened up. If the nose had retreated too, the beast could not have kept contact with the earth; but the nose retained its old length, or got longer, and hung down loosely in front.

Again, the horse presumably started with five toes per foot like ourselves, a primitive feature shared, for instance, with dogs. At any rate an early ancestor of the horse has been recognised with four toes on the front foot and three behind (Fig. 238). From that stage the record is complete. Gradually, through the generations, all except one toe per foot withered away. In the horse, as we know it, much of what looks like leg is made of a single toe, with mere vestiges of two other toes on either side. The hoof is the nail of this single toe. In cows, which have kept two toes per leg, the hoof is double.

The following systems are recognised in the Tertiary:

Pliocene—Major proportion of living molluscs
Miocene—Minor ,, ,, ,, ,,
Oligocene—Few living molluscs
Eocene—Dawn of living molluscs
Paleocene—More ancient than Eocene.

The *cene* of these names is derived from the same Greek word as the *kain* of Kainozoic, and means recent. The meaning of the prefixes, from Eocene onwards, is as explained above—dawn, few, minor, major.

Paleocene deposits have not been recognised in Britain. In America they have yielded a distinctive mammalian fauna, as has already been indicated in Chapter LIV.

EOCENE

During the ages, from Devonian times onward, Scotland has generally been more terrestrial, and often more volcanic, than England. This holds in Early Tertiary times, when the Hebrides and Antrim were a terrestrial volcanic district, and the South-East of England an estuarine or marine district reaching continuously from the London region southwards into France and Belgium.

The Eocene of South-East England is grouped as follows:

Upper Eocene	Bagshot Sands
Lower Eocene	London Clay Woolwich and Reading Beds Thanet Sands

The THANET SANDS are marine and only developed in the London district and to the east; the WOOLWICH AND READING BEDS are marine to the east and estuarine to the west; the LONDON CLAY is marine throughout its outcrop right into Hampshire.

The BAGSHOT SANDS are marine. They are responsible for many heaths standing well above the low country of the London Clay: Hampstead, Aldershot and Bagshot. To show how these formations continue into the continent we may point out that the London Clay is identical with the Ypres Clay, often called the Ypresian, and that neighbouring hills, which were of great importance in the War, are made of Bagshot Sands.

The life of the Eocene in the London area is characterized by tropical palms, turtles and crocodiles, with numerous lamellibranchs and gastropods.

In the Tethys, as seen in the Alps, Egypt and the Mediterranean generally, the large foram *Nummulites* (Fig. 117A) flourished exceedingly, building great limestones.

We may now turn to the volcanoes of North-East Ireland and the Hebrides. Their Tertiary age is certain because of associated leaves of plants, found especially in Mull; but it is very difficult to determine plants precisely by means of their leaves, and it is often found that plants do not serve as very good zone fossils in fixing geological age. At present it is thought that the Hebridean volcanoes were of Eocene date. They certainly are old enough to have lost all original volcanic form through erosion. Their plutonic rocks, such as the granites of the Mournes and North Arran and the gabbros of the Cuillins in Skye, have been exposed and carved into their present form. Such plutonic masses probably represent the basal wrecks of great volcanoes. Plutonic centres, besides those of the Mournes, Arran and Skye, occur in Mull, Ardnamurchan and St. Kilda.

The Tertiary volcanics rest disconformably upon uplifted Upper Cretaceous rocks, or underlying Jurassic. In Antrim the succession of black basalt lavas on white chalk is extremely conspicuous. In the Hebrides, though Upper Cretaceous rocks are found at many places, they are generally too thin to make a feature in the landscape.

The lavas are mainly basaltic, and include the famous columnar basalts of Staffa and the Giant's Causeway. They very often give trap featuring, except where cloaked in boulder clay as in Antrim or baked near plutonics. They were poured out on land, as is witnessed by the frequent intraformational weathering of lava tops to lateritic soil before each in turn was covered by the next lava of the sequence. The laterite is generally ferruginous, but in Antrim bauxite has been developed on one horizon, as well as ironstone, and has been worked as an ore of aluminium. The few fossils found are usually leaves of land plants. In Mull the forty-foot trunk of a tree stands vertically, submerged and charred, in a basalt lava, to be ages afterwards re-exposed by marine erosion. It is known as Macculloch's Tree, after its discoverer, and in 1932 was given to the nation with the district in which it stands.

A complex pitchstone lava in what is now the island of Eigg occupied a valley eroded in the ordinary basalts. The valley walls have since been removed by further erosion, and the more resistant pitchstone has been left to dominate the scene (Fig. 322).

While most of the Tertiary lavas of Britain are terrestrial, there is a central area in Mull, with a diameter of 5 miles, in which a very thick succession of pillow lavas has accumulated. There is no doubt that these lavas must have flowed into water. They are interpreted as marking the site of a crater lake, that formed intermittently on the bottom of a caldera, frequently renewed by subsidence.

Another feature of great interest in Mull is a region of pneumatolysis, marked by the universal decomposition of the olivine of the lavas and by other chemical changes. This region of pneumatolysis has a diameter of 16 miles, and surrounds the caldera already mentioned. Outside its limit it is extremely easy to find fresh olivine in the lavas, but inside it is impossible. The changes are due to hot vapours issuing from the central part of the volcano.

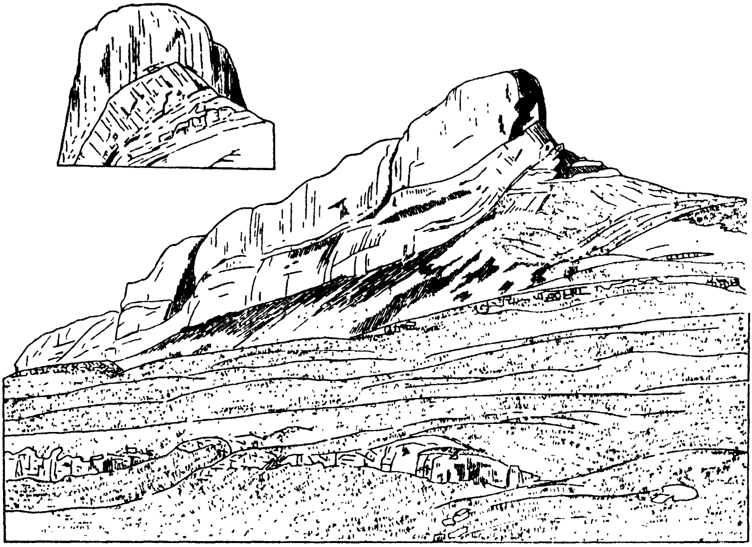

FIG. 322. The pitchstone ridge of the Scuir of Eigg. (A. S. Reid and S. H. Reynolds photos.)

It would take a book to tell of all the other remarkable points in the geology of Mull. Here mention can only be made of five :

Necks of volcanic agglomerate figure on a very large scale within the region of pneumatolysis.

Ring-dykes are abundant. Most of them are concentric with the caldera that is marked out by pillow lavas ; but there is also a second centre.

Cone-sheets are extraordinarily numerous. They are arranged about the same two centres as the ring-dykes.

There is a group of circumferential folds, both anticlines and synclines, surrounding the caldera of subsidence that contains the pillow lavas. They seem to have been developed by the outward push of a granophyre ring-dyke rising up around the caldera.

A great swarm of north-west basalt dykes is focussed on Mull. It has about the same width as the region of pneumatolysis.

OLIGOCENE

Oligocene is mainly represented in Britain by estuarine deposits in the Isle of Wight. The rocks are mostly marls and fresh-water limestones. They are conformable to the Eocene. Their fossils are land plants, fresh-water snails and lamellibranchs, and occasional marine shells such as oysters.

An outlier at Bovey Tracey in Devon consists of clays and lignites.

In the Tethys, nummulitic limestones continued as a great feature of the Oligocene. They are well displayed in the Alps and in Mediterranean countries.

MIOCENE

Little or nothing is known of Miocene deposits in Britain. The period was one of upheaval, with gentle folding responsible for the London and Hampshire Basins and the intervening Weald Dome. Locally the folding became acute, as in the Isle of Wight, where a very steep limb separates two very gently inclined limbs. Such a fold is called a monocline. In Dorset the continuation of the Isle of Wight monocline is complicated by faulting.

The widespread upheaval and local folding of Britain were contemporaneous with intense folding farther south in the Tethys region. The folding of the Jura Mountains and much of the folding and thrusting of the Alps themselves are of Miocene date. In the case of the Alps important beginnings had been made in Oligocene and Eocene times.

The great modern chains of the Mediterranean belt, from the Pyrenees, through Alps, Carpathians, Caucasus, Persia, Himalayas, Burma, are in large measure of Tertiary date. So too are the great Circum-Pacific chains, including the Rockies. The development of these chains has not quite ceased, as is shown by the prevalence of earthquakes along their course. The modern volcanic phenomena often found along these Tertiary chains reminds us of the Scottish Devonian volcanics and granites along the Caledonian Chain, and of the Devon Permian volcanics and granites along the Hercynian Chain.

PLIOCENE

A small area of Pliocene deposits occurs in East Anglia. It is clear from an inspection of the map of Britain that these Pliocene rocks are later than considerable folding and erosion of the neighbouring Eocene of the London basin. They rest unconformably, partly on the Eocene, but mainly on the underlying Chalk.

They are divided into :

Cromer Forest Bed
Various marine Crags

Crag is a local name for shelly deposits ; and the Pliocene Crags of East Anglia are largely unconsolidated shell-banks.

Many of the species of lamellibranchs and gastropods of the Crags belong to living species, though comparatively few still inhabit British waters. In the earlier Crags there are numerous Mediterranean species, which indicate that British waters were warmer than to-day, though not nearly so warm as during Eocene and Oligocene times. Gradually the climate got cooler ; and the last of the Crags contains a number of arctic species. Various members of the Pliocene have furnished flints that are generally admitted to show human workmanship.

The Cromer Forest Bed Series is an estuarine or deltaic deposit, perhaps indicating a northward extension of the Rhine. It contains much driftwood and other plant remains, which may have floated downstream for many miles. Most of its plant species are known in Norfolk at the present time ; but in the interval Norfolk has been completely under ice during the Pleistocene. In so far as these drifted plants correspond with the local climatic conditions of Cromer Forest times, they suggest something more genial than what is indicated by the shells of the immediately underlying Crag. A large fauna has been collected. Most of the mammals are extinct, and include the fierce sabre-toothed tiger.

A marine shell bed, with a return of arctic species, intervenes between the Cromer Forest Bed and the boulder clays of the Pleistocene.

TERTIARY ECONOMICS.—The sedimentary deposits of England are dug for clay, including pipeclay, and sand, and, at Bovey Tracey, lignite. The igneous rocks of Scotland and Antrim yield road metal. A zone of lateritic weathering in the Antrim basalts provides both bauxite and iron ore. The haematites of Cumberland and Furness, mostly replacing Carboniferous Limestone, are now thought to be of Tertiary age.

CHAPTER LXXIII

QUATERNARY

THERE has been comparatively little change in the molluscan life of the world during Quaternary times, except as a result of migration ; but many of the mammals of the Pleistocene, like the mammoth (Fig. 323) and woolly rhinoceros (Fig. 15), did not survive into Recent times. The distinguishing feature of the Quaternary as a whole is the conspicuous presence of intelligent man. He has left us very few of his own bones (Fig. 242), but much in the way of weapons, tools, pottery, etc., grouped under the title artifact (Fig. 244). The study of these in relation to their geological environment has allowed specialists to divide the Quaternary into a number of cultural stages. The principle employed is similar to that used in the establishment of other fossil zones : in a series of undisturbed culture-deposits, the overlying layers are younger than the underlying layers.

FIG. 323. Young mammoth mounted in Leningrad Museum in the struggling attitude in which he was dug out of the frozen mud of Siberia. The end of his trunk was devoured by dogs at the time of his exhumation.

The broad divisions recognised in Europe are :

RECENT	Iron Age (from which is generally separated most of the Christian era) Bronze Age Neolithic Age, with polished flints Mesolithic Age
PLEISTOCENE	—Palaeolithic Age, with no polished flints

The Pleistocene was of very much greater duration than the Recent, although the development of human culture during its span was much less marked. The Mesolithic Age is difficult to define in a few words. It is characterized, partly by the nature of its flint artifacts, and partly by the associated animal remains.

The Pleistocene has particular interest for geologists, since it was the Great Ice Age or Glacial Period. As noted already the Pliocene deposits of East Anglia show a much cooler climate than the Eocene of the London area, and also record a fairly progressive fall of temperature within their own time. With the oncoming of the Pleistocene this drop in temperature became glacial, and much of northern Europe and America accumulated ice-sheets.

Though profoundly altered in detail, the general form and the coastline of Britain are much the same now as they were a little before the Ice Age. Modified pre-Glacial sea-cliffs are often recognizable, either within, or just beyond, the range of the present waves. The evidence is particularly clear in certain cases described from glaciated districts of England, Ireland and Wales. In several localities beach deposits have been found a few feet above sea-level, buried under scree, at the foot of rounded cliffs, the whole coated with boulder clay. The rounding of the cliffs is of pre-Glacial date, and attributable to weathering after upheaval had interrupted the basal attack of the waves.

The English Channel lies outside the field of glaciation ; but it shows what is evidently the same scree-covered beach at the foot of rounded cliffs in several sheltered situations a few feet above sea-level. It is clear that the cliffs of the Channel were in large measure cut by the sea in pre-Glacial times, and that they have been protected from wave action, during part of the intervening time, by elevation.

Whether the Straits of Dover were formed in pre-Glacial times is not certain. It is quite possible that the Straits were excavated by an immense river draining the confluent glaciers of Scandinavia and Britain, and receiving the Rhine as a tributary.

During Pleistocene times all the northern part of what is now the North Sea was occupied by the Scandinavian ice-sheet. It came ashore in Britain from Durham southwards to East Anglia, penetrating far inland in the neighbourhood of Cambridge. For the most part, Scandinavian ice was prevented by native ice from touching Scotland, south of the Orkneys and Shetlands. The Scottish ice radiated out in all directions from the Highlands. As it approached the east coast its currents were affected by the push of the Scandinavian ice, and parted, to flow north and south. The parting occurred, during part of the period at any rate, at the Firth of Forth.

The portions of Britain actually invaded by Scandinavian ice are mapped out by the distribution of Norwegian boulders. The paths of various currents within the British portion of the confluent ice-sheet are similarly indicated by trains of particular British erratics, and also by striae, roches moutonnées and drumlins. The problem is very complicated because the directions of the ice currents varied from time to time. Thus in the Highlands, at early and late stages of the glaciation, the ice took the form of valley glaciers flowing down the valleys ; but, at the maximum glaciation, it moved as an ice-sheet, independent of the local valley systems. Similarly, the ice-sheet that traversed the site of Glasgow did not flow west, as the Clyde does to-day, but east across the watershed, towards Edinburgh.

At the maximum glaciation Scottish ice not only succeeded in excluding most of the Scandinavian ice, but also invaded northern Ireland and much of England.

An area, such as Scotland, where local ice has excluded invasion, may be called a sanctuary. Within Britain there are several minor sanctuaries. The mountains of Skye, the north part of Arran, much of the western Southern Uplands, the English Lake District and the major part of Wales have all kept themselves free of erratics derived from the mainland portion of the Scottish Highlands (Fig. 324).

Since Britain had much the same coastline in pre-Glacial times as to-day, the currents of the ice-sheet often passed across parts of the old sea bottom and picked up shells. For instance the Highland ice, after reaching the Moray Firth, was deflected north-west over Caithness by Scandinavian ice, and deposited great spreads of shelly boulder clay. Similarly Scottish ice, after crossing much of the Irish Sea, pushed forward into parts of North Wales. A rather complicated case is afforded by Highland ice that crossed the Bay of Ayr and then turned inland. At a later stage Ayrshire ice-currents flowed seaward into the Bay of Ayr, and moulded and striated the country accordingly ; but they did not succeed in putting back all the sea-shells carried inland by the early currents.

In the South of England, beyond the limit of maximum glaciation, Palaeolithic man and extinct Pleistocene mammals, such as the mammoth and woolly rhinoceros, have left abundant remains in the gravels of the Thames and other rivers, and in caves.

Farther north such remains are often found in beds intercalated between boulder clays, or they may occur as actual inclusions in boulder clay. A terminal moraine runs east and west at York. North of this moraine

Palaeolithic man is not definitely known (except perhaps his very latest representative), and mammoths, etc. are very rare. It appears, therefore, as might have been expected, that Scotland was much more continuously under ice during glacial times than England. Even so, mammoth remains have been found under boulder clay in Ayrshire, and a tusk in boulder clay near Edinburgh; also a bone of woolly rhinoceros has been discovered in glacial gravel near Kirkintilloch.

In the South and Midlands of England it is common to find that a large proportion of the pebbles near the surface have been up-ended by long continued repetition of freezing and thawing. This phenomenon is not found in Scotland, where tundra conditions do not seem to have lingered after the disappearance of the last glaciers.

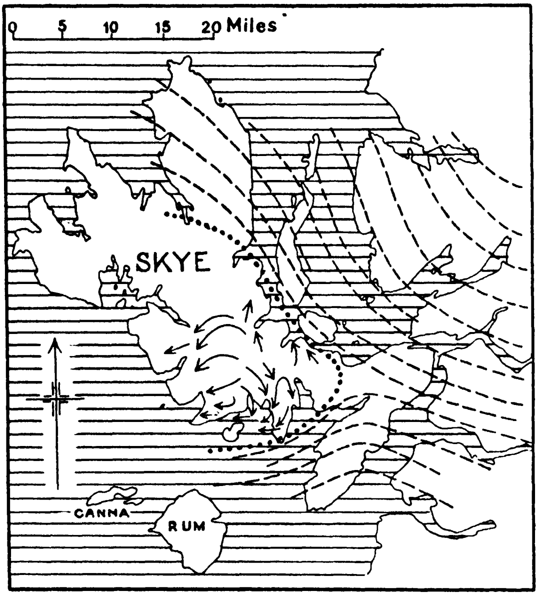

FIG. 324. Skye sanctuary, defined by heavy dots. Broken lines indicate direction of ice-flow from mainland; arrows that of local origin. (After Harker, 1902.)

While the main glacial feature of Europe was the great confluent Scandinavian-British Ice-Sheet, the Alps were covered under a quite separate cap. The Alpine glaciation is supposed to show four distinct glaciations, separated by interglacial periods marked by deposits containing fossils indicative of genial conditions. A similar story seems to be furnished by the south-east of glaciated England and elsewhere. The cause of the Great Ice Age has not yet been decided; and it seems all the more difficult to explain in face of alternations of glacial and mild interglacial climates.

The greatest area of Pleistocene glaciation was in North America. The ice-sheet there had three centres of dispersal, one on either side of Hudson's Bay, and another in the western mountains. All Canada and the northern States were covered. Here again are impressive evidences of mild interglacial periods.

Many mountainous regions in other parts of the world, both in the northern and southern hemispheres, show the effects of Pleistocene glaciation.

Outside the regions of glaciation, changes of Pleistocene climate are often shown by records of rains. Thus during a pluvial period the Great Salt Lake of America expanded, as witnessed by wave-cut terraces, deltas, shingle-spits and bars. Numerous strand lines occur up to 1000 feet above the present level. The top strand corresponds with an outlet, which was rapidly cut down several hundred feet, with a width of a third of a mile. Later, following a return of desert climate, the lake shrank away from its outlet to the limits that we see to-day.

It has already been explained how glacial conditions led to widespread deposition of loess across Eurasia and North America, with the Thames valley brick-earth as a possible British representative.

The life of the Pleistocene was remarkable both in Europe and North America for various kinds of elephants. In Europe we also find hippopotamus and rhinoceros. In America the elephants are associated with other forms now native only in the Old World, such as horses and camels. At several times during the Kainozoic, America and Eurasia must have been connected, probably across the site of the present Behring Straits.

Wherever we go, the succession of life in any one district may be extremely complex, for changes of climate led to great migrations as well as to extinctions. Some of the elephants and rhinoceroses wore long woolly hair, and were adapted to extreme cold. The mammoth was of this type, and his frozen carcase is occasionally found in perfect preservation in Siberia. Towards the close of Pleistocene times the reindeer was extremely abundant in Britain and most of Europe.

The artifacts of Palaeolithic man vary in fashion according to their date. Palaeolithic man lived in Europe during the Glacial Period, including the interglacial intervals ; he was companion to the great mammals mentioned above. The few finds of bones belonging to early Palaeolithic man excite intense interest. One of the most famous fossils is the missing link, *Pithecanthropus*, discovered in Java. Another outstanding find is Pekin man. Late Palaeolithic man was a very skilful artist. He has left beautiful sketches of mammoth, reindeer, etc., engraved on bone and ivory ; within recent years many of his paintings have been recognised on the walls and roofs of caves in Spain (Fig. 243).

LATE GLACIAL AND POST-GLACIAL

While Scotland was wholly under ice during the maximum of glaciation, there was a long Late Glacial stage when the lower grounds were clear. We have already considered the interference with river drainage that characterized this period (Chapter XXXVIII). Here we may turn to another side of the subject. During part of Late Glacial times most of Scotland stood about 100 feet lower than to-day. Bedded clays containing arctic shells collected in sheltered estuaries like the Clyde, and shingle beaches on exposed shores like those of the island of Jura. The marine deposits of this time are now elevated with a coast line roughly 100 feet above sea-level, and are called the 100-foot beach deposits (Fig. 325). The elevation has affected most of the mainland of Scotland and many of the islands, but not the Outer Hebrides, Orkney or Shetland.

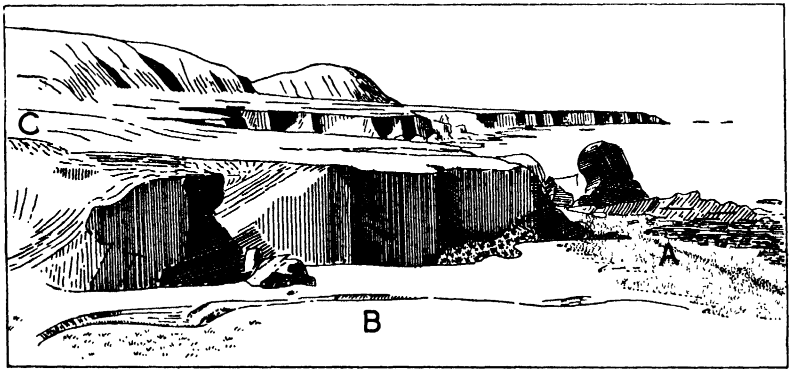

FIG. 325. Raised beaches two miles W. of Rhuvaal, Islay. (Geol. Surv. photo.) A. Modern storm beach ; B. Post-Glacial 25-ft. beach ; C. Late-Glacial 100-ft. beach.

The disappearance of the ice was not a uniform process. For instance, there is evidence of a well marked readvance, known as the Loch Lomond readvance. The Loch Lomond glacier had melted away, allowing the 100-foot beach clays to be deposited in the basin. Then the glacier reformed and pushed the clays forward under it, mixing them up into shelly boulder clay. The frontal moraine of this readvance has been traced for many miles as a low but persistent ridge. It crosses, near the summit, the hill road that connects Helensburgh on the Firth of Clyde with Balloch on Loch Lomond.

The elevation of the 100-foot beach took place in steps ; and a number of Late Glacial marine strands can sometimes be recognised. They are seldom conspicuous. The raised beach that makes an almost continuous feature around the coasts of Scotland at 20 to 50 feet above sea-level is of

Post-Glacial date and belongs to Mesolithic, or as they are sometimes called Early Neolithic, times. This raised beach furnishes a conspicuous terrace of shingle and sand, often backed by cliffs with caves, in one of which, in Arran, Bruce learnt his lesson from a spider.

The material of this beach at some localities in Scotland rests upon peat or forest growths that continue under present-day sea-level. This indicates a previous, but still post-Glacial, elevation of the country above its present position.

The sea shells of the Mesolithic beach are species found along our coasts to-day. Man lived on the margin of the sea. His weapons, tools, and refuse heaps of shells are well known ; occasionally even his canoes have been found. He also lived in the caves of the beach, as at Oban, when the sea began to retreat.

ECONOMICS.—The economic products of the Quaternary are of very considerable importance. They include gravel, sand, brick clay, peat, diatomaceous earth, and a large proportion of the water used in agricultural districts.

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