A

TEXT-BOOK OF GEOLOGY

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BY

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PREFACE TO THE FIRST EDITION

A TEXT-BOOK such as the present falls naturally into two sections which, for brevity, may be called Physical Geology and Stratigraphical Geology respectively. The first section, Chapters I to XV inclusive, has been written by Mr. Rastall; the second section, from Chapter XVI to the end, has been written by Mr. Lake. Each author is responsible for his own section only, but care has been taken to prevent omissions and to avoid any repetitions beyond what would be necessary in a work by a single author.

In the preparation of the book the authors have received assistance from many friends to whom they desire to express their acknowledgements.

In the Physical section Mr. C. Barrington Brown jun. helped in the final revision of the manuscript for the press and drew most of the diagrams which appear in this part of the book. In Mr. Rastall's absence abroad Mr. J. Romanes kindly corrected the proofs of this section of the book. Dr. Hatch also read the proofs and offered many valuable suggestions.

In the Stratigraphical section the thanks of the authors are due especially to Mr. Henry Woods, who read the whole of this part in manuscript with the exception of the last chapter. The book has profited greatly from his advice. Mr. F. W. Harmer very kindly read the account of the Pliocene series and added many useful notes.

Many of the illustrations are original. The sources of the others are acknowledged in the book, and for permission to reproduce them the writers are indebted to the original authors and to the Councils of the Societies in whose publications they have already appeared. The map of the Pliocene shore-lines (Fig. 129) was drawn specially for this work by Mr. Harmer and to him accordingly the authors are particularly indebted.

P. L.
R. H. R.

October, 1910.

PREFACE TO THE THIRD EDITION

CONSIDERABLE alterations have been made in this edition, and the book has been revised throughout. The account of coral reefs has been modified in accordance with recent work upon the subject, and the chapter on Ore Deposits has been entirely rewritten. A new section on Concretions has been added to Chapter IX, and new sections on Petroleum and Natural Gas have been written by Mr. James Romanes. In the Stratigraphical section the account of the Carboniferous System has been largely rewritten, and a new chapter on The History of Igneous Activity in the British Isles has been added. The new chapter has been written by Mr. Rastall, but otherwise the responsibility of the authors for their respective sections remains as in the first edition.

These are the most important changes, but many smaller corrections and alterations have been made throughout the book.

P. L.
R. H. R.

May, 1920.

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A TEXT-BOOK OF GEOLOGY

CHAPTER I

INTRODUCTORY

The main object of the science of geology is the study of the structure and history of the earth. For this purpose we have to take into account the changes which have taken place in the past in the earth itself and in its inhabitants. It is the fundamental doctrine of modern geology, as enunciated by Lyell, that the study of the present is the key to the past, and to understand thoroughly what has taken place in past ages we must first gain an acquaintance with the earth in its present condition. The processes which are now taking place, both on land and in the sea, are the same in kind, if not in degree, as those which have always taken place since the earth first attained to something resembling its present state. The earliest stages in the history of the earth are unknown, and, as a matter of fact, geology, in the proper sense of the word, is not concerned with them; nor is it concerned with the earth's place in the solar system and its relation to the other planets. All these belong to astronomy and mathematical physics.

It is evident that geology can be approached from several sides, such as the geographical, the chemical and physical, and the biological. The sciences of physical geography and physical geology are closely allied: the former is concerned more particularly with external forms, whereas the latter pays greater attention to internal structures, but their methods are very similar, and are gradually becoming more and more so.

Acting on Lyell's principle of Uniformitarianism we naturally begin with the study of the earth as it exists to-day and the processes which are now occurring in the parts accessible to us. This constitutes the domain of Physical Geology, which deals more particularly with the forms assumed by masses of land and of water and with the origin and development of those forms. The constitution of the earth's crust, and its chemical and physical properties, are dealt with by Petrology; Palæontology deals with the remains of the animals and plants of former times, the evidence they give us as to the conditions of the past, and the evolution of organic beings on the earth; while Stratigraphical Geology avails itself of the facts derived from a study of all the other branches, and applies them to the explanation of the structure of the earth as a whole. Stratigraphy may in fact be regarded as the unravelling of the history of the earth.

From the geological point of view the earth may be regarded as consisting of three concentric zones, or spheres, of very different nature: these are the atmosphere, the hydrosphere, and the lithosphere. The atmosphere is a continuous layer of gases, surrounding the whole globe and of indeterminate outward extension. Within it are to be found locally substances in other than the gaseous form, and notably water in the liquid or solid state, forming clouds, rain, snow, &c., and the whole is in a state of continuous movement. The hydrosphere differs from the other zones in that it is discontinuous. It comprises all the water which lies on the surface of the earth, not only the great oceans and seas, which are all in direct communication with each other, but also the water system of the land, ranging from great lakes and rivers down to the smallest pool. Some of these masses are entirely cut off from all direct connexion with the oceans and can only communicate with them indirectly by way of the atmosphere. The third of these zones, the lithosphere, comprises the solid earth, and it is the province of geology to investigate its structure and history. The study of the other zones is of importance only in so far as it throws light on the processes which have built up the outer crust of the earth as we now see it. It is, however, impossible to draw any hard and fast line between the domains of physiography and geology: the two sciences overlap and merge into one another insensibly. The geologist is also for the most part concerned only with the outermost portion of the globe. The part which is open for our inspection is but a small fraction of the whole, and at the present time little or nothing is definitely known as to the condition of the earth's interior, beyond the limits of mines and borings, and the question still remains very much in the hands of the physicist and the astronomer.

The three zones as above defined are very closely connected among themselves and there is a constant transference of material from one to the other. All water surfaces exposed to the air are continually undergoing evaporation, and thus the water is transferred from the hydrosphere to the atmosphere. The reverse process is also constantly in progress, as is shown by the fall of rain and snow and the deposition of dew. Water also exercises a solvent action on some of the constituents of rocks, and the dissolved material passes from the lithosphere to the hydrosphere. Direct transfer between the atmosphere and the lithosphere is of subsidiary importance, but occurs in certain chemical reactions, and in connexion with volcanic phenomena. It would be easy to go on multiplying instances of this transfer of material between the different zones, but enough has been said to show that a close connexion exists between them.

The Atmosphere.—The atmosphere consists of the mixture of gases which is commonly called Air. The air is a mixture in the chemical sense; that is to say, the gases are not present in fixed and definite proportions by weight, but the composition may vary, though the amount of variation which actually occurs is but small. By far the most abundant constituents of air are oxygen and nitrogen, which form on the average about 98·5 per cent. of the whole. Other important constituents are water-vapour and carbon dioxide, and some hydrogen and small traces of ammonia and nitric acid are always present. These are the chief constituents of pure air under normal conditions. But in the air of towns other substances are found in perceptible quantities, such as compounds of sulphur, and many other gases, the products of combustion and innumerable industrial processes. During volcanic eruptions unusual gases are often evolved in enormous quantities, and may cause considerable temporary variations in the composition of the air in their neighbourhood. Recent research has shown that the gas which was formerly regarded as pure nitrogen really contains a small proportion of certain other elementary gases, argon, helium, krypton, &c., which are only separable from it with great difficulty. All these gases are singularly inert and are of no practical importance, at any rate from the geological standpoint. For our present purpose the atmosphere may be regarded as consisting of a mixture of oxygen, nitrogen, carbon dioxide and water-vapour, in approximately the following proportions:—

	Per cent.
Nitrogen	77·91
Oxygen	20·66
Water-vapour	1·40
Carbon dioxide . . .	·03
	100·00

The nitric acid and ammonia generally amount to about one part in a million.

It has already been pointed out that the amount of water-vapour in the atmosphere is far from constant: a continual transference is taking place in this respect between the atmosphere and hydrosphere, in both directions. Water is continually being removed by evaporation into the atmosphere, and carried from place to place by air-currents.

Sooner or later it is again condensed into the liquid or solid form and falls as rain or snow, and thus completes its cycle of transformation. This constant circulation of water between the two spheres is of enormous importance, since it constitutes the machinery of the most important of all geological agents, viz., running water. Rain falls on the land, and under the influence of gravity, obeying the ordinary laws of liquids, it tends to seek the lowest possible level, thus forming the great network of streams, rivers and lakes, which covers the surface of the land, and also maintaining the ocean itself at a generally constant level.

The air does not remain at rest but is in a constant state of motion. When this motion is sufficiently active to be perceptible to our senses it is called wind, but besides this there is a constant imperceptible circulation in the air, and especially a rise of warm air and descent of cold air, by virtue of variations of density induced by changes of temperature. It is impossible here to enter upon a detailed consideration of the winds and the whole class of phenomena, which may be summed up in the convenient, if somewhat vague, term, Weather. It must suffice to say that the most important factors in producing meteorological changes are variations of the pressure and temperature of the air. If the air in two adjoining areas is at different temperatures and under different pressures, there will be a transfer of matter from one to the other, tending to restore equilibrium, and the result will be wind. These air-currents or winds transfer water-vapour from one place to another, and under the influence of a fall of temperature this water forms rain or snow. Hence wind has an important geological action by virtue of its carrying powers. But wind also possesses a certain dynamical force of its own, and may act as an agent of destruction. In a great storm it is clear that much material is often moved from place to place. Great changes are often wrought in the face of the country by the power of the wind alone, and this work must have its own geological effect, either direct or indirect. Ordinary winds must also exert a similar influence in a less degree ; and, indeed, the wind is a geological agent of no small importance.

The directions of the air-currents are not purely arbitrary but are governed by certain laws.

Primarily they are determined by variations of temperature and pressure in different parts of the earth's surface, and especially by the distribution of temperature-zones, parallel to the equator. If this were all, we should expect the heated air of the tropics to rise, while its place would be taken by a current of cold air flowing in from the direction of the poles, so that at the surface there would always be a wind from the north in the northern hemisphere and from the south in the southern hemisphere, while in the upper regions of the air the directions would be reversed. But the matter is complicated by other factors, and especially by the rotation of the earth on its axis, the irregular distribution of land and sea, and the diminution of the circumference towards the poles. Consequently the actual course pursued by these major air-currents is a curved one. In the northern hemisphere the direction of movement is counter-clockwise, in the southern hemisphere clockwise. Thus in the northern hemisphere the warm, damp winds from the tropics blow from the south-west, while the cold arctic current comes from the north-east. In the more open parts of the oceans these directions are maintained with a fair amount of regularity, especially those of the currents blowing towards the equator, which are known as the Trade Winds. But over the continental areas the conditions are too complex for any uniformity to be maintained. The direction of the winds is affected by the distribution of land and sea, by variations in the relief of the land and innumerable other local causes, so that the utmost irregularity prevails. This irregularity of the winds produces variations also in rainfall and temperature, and the sum of these variations may be expressed by the word *Climate.* Climate is very important geologically and produces marked effects, as will be shown in detail later on.

The Hydrosphere.—This includes the whole body of water existing as such on the surface of the globe and in the interstices of the lithosphere. It has been already pointed out that there is a constant interchange between this and the atmosphere, and as a result of numerous chemical processes there is also much interaction in this respect with the lithosphere. Processes of hydration and dehydration are continually going on, and water is constantly being absorbed or set free as a result of chemical actions. Many minerals and rocks also contain water, either absorbed or in combination, but with this part of the subject we are not now concerned. It is necessary now only to deal with the visible water, which exists as such either in the liquid or the solid form.

Natural water is commonly regarded as of two kinds, fresh water and salt water, but this distinction is an artificial one, and cannot be maintained. All waters contain a certain amount of saline matters in solution, and the difference is only one of degree. The waters of the sea and of certain lakes contain such a high proportion that it is perceptible to the taste, but in the case of many of these lakes it is clear that their excessive degree of saltness has been produced by concentration of the salts contained in so-called 'fresh' water; and the saltness of the sea is probably due to the same cause, viz., concentration of soluble material brought down from the land during innumerable ages.

There is at any rate one distinction between salt and fresh water which is important for our present purpose, and that distinction is a biological one. The inhabitants of salt and fresh water are markedly different, and this fact is of great geological importance.

For all practical purposes, then, the hydrosphere consists of two principal parts, the oceans and seas, and the water-system of the land. The former is continuous, since all its parts are in direct connexion ; the latter is not, but consists of innumerable detached portions, scattered over the surface.

The oceans cover about 72 per cent. of the whole surface of the globe, or just over 143,000,000 square miles, but over a certain proportion of this area the water is comparatively shallow. Soundings show that in very many cases the submarine slopes surrounding the great land masses are very gradual down to a depth of about 100 fathoms, and then the gradient suddenly becomes much steeper. It has, therefore, come to be customary to regard the true boundary between the continental plateaux and the ocean basins as occurring at the 100-fathom line, rather than at sea-level. The area of this submerged part of the continents is about 10,000,000 square miles. After this adjustment, therefore, the total area of the ocean basins is about 133,000,000 square miles and that of the continents 64,000,000 square miles, or approximately in the proportion of two to one.

The floor of the oceans is by no means uniform, but is diversified by plains, valleys and hills, somewhat like those of the land, and the greatest depth attained by the ocean below sea-level is closely comparable with the greatest height reached by the land ; the deepest known sounding is in the Pacific, near Guan I., one of the Ladrone group, where a depth of 5,269 fathoms or 31,614 feet was found. Other great depths occur south of the Tonga Islands and north-east of New Zealand, 5,155 fathoms, in the Challenger Deep near the Caroline Islands, 4,475 fathoms, and the Tuscarora Deep off the east of Japan, 4,655 fathoms. It is worthy of note that the deepest soundings are often comparatively close to land : thus soundings of over 4,000 fathoms have been found within fifty miles of the coast of Peru. This signifies that sub-oceanic slopes are often exceedingly steep. Many attempts have been made to estimate the average depth of the ocean, and it probably lies somewhere between two and three thousand fathoms.

As in the atmosphere, so also in the seas there is constant movement going on, at any rate in the parts directly accessible to observation. It is probable that in the deeper parts of the great ocean basins this movement is very small indeed, but at and near the surface the water is in constant motion. This motion is of several kinds : there are the purely superficial movements of the waves, which are due chiefly to the wind ; somewhat more deep-seated are the effects produced by variations of temperature, assisted to a considerable extent by wind action; this results in the production of currents. The direction of flow of these currents is greatly modified by the form and distribution of the land-masses, but on the whole it corresponds fairly well with the directions of air movement. The dominant feature of the whole is a flow of warm water from the equatorial regions towards the poles and a corresponding return flow of cold water towards the equator. These currents produce very important effects on climate, though perhaps less than was formerly believed; and in particular it appears that the influence of the Gulf Stream on the climate of Western Europe has been greatly exaggerated. The warmth of this region is probably to be attributed to wind-currents rather than to sea-currents. The third great disturbing element in the waters of the ocean is the attraction of the sun and moon, especially the latter, on this great mass of mobile liquid, which gives rise to tides. This causes not only a rise and fall of level, but also produces well-marked currents, which differ from the class previously mentioned in being inconstant in force and direction. The geological and climatic effects of these movements of the waters of the ocean are of great importance, as will be seen in later sections.

It has already been mentioned that sea-water contains a considerable amount of various soluble salts. This proportion is not constant, but is influenced by local causes. Thus in a partially enclosed area in a warm climate there is considerable loss by evaporation, so that the solution tends to become more concentrated. For this reason the Mediterranean is more salt than the average. Again, if a large number of rivers flow into a partly enclosed basin, where evaporation is small, the solution will become more dilute, and the water may even come to be merely brackish, as in the case of the Baltic and other inland seas. But these are merely local variations on a small scale and the composition of the waters of the open ocean is fairly constant.

According to the Reports of the *Challenger* expedition, 1,000 parts of water from the open ocean contain about 34·4 parts by weight of mineral matter, and the percentage composition of this dissolved matter is shown in the following table.

	Per cent.
Sodium chloride	77·758
Magnesium chloride	10·878
Magnesium sulphate	4·737
Calcium sulphate	3·600
Potassium sulphate	2·465
Magnesium bromide	·217
Calcium carbonate	·345
	100·000

It will thus be seen that by far the most abundant constituent is sodium chloride, and salts of magnesium are also very abundant. Calcium occurs in less quantity; but the compounds of this element play a very important geological part, and in particular calcium carbonate is absolutely essential for building up the structures of a large proportion of the living inhabitants of the sea.

Besides this solid matter sea-water also contains dissolved gases. These gases are essentially the same as those of the atmosphere, but they occur in very different proportions. Since the solubility of gases in water is increased by pressure it follows that the amounts occurring in the deeper parts of the sea must be much greater than near the surface. It is unnecessary to enter into any details as to these dissolved gases, and it must suffice to say that the only ones of any practical importance are oxygen and carbon dioxide, which are closely concerned in the vital activity of animals and plants.

The Lithosphere.—Before we enter in detail into a consideration of geological processes and their results, it is necessary to have some preliminary acquaintance with the material on which they have to work. It is impossible rightly to understand the mode of action of any force unless we know the nature of the substances acted on, since the same agency may produce totally different results under different circumstances. In the first place, therefore, we shall give a brief and condensed account of the structure and composition of the most important features of the earth's crust, leaving full details for subsequent sections. This course may involve a certain amount of repetition, but this is probably unavoidable in any case.

The Lithosphere or solid part of the earth, so far as it is open to our inspection, consists of *rocks*, and it is necessary to understand clearly what is meant by this term. A rock may be defined as *an aggregate of mineral particles*, without any reference to its state of cohesion. As usually understood the term conveys an idea of hardness, but this is unessential. To the geologist, loose sand or soft plastic clay are rocks just as much as the hardest granite, and the hardness is usually a secondary or superinduced character.

As will be seen from the above definition, before we can proceed to the consideration of the rocks as such it is necessary to have some acquaintance with the minerals of which they are composed. Minerals are substances which have a definite crystalline form and a more or less definite chemical composition, and the number which are known to exist is very great. The majority of these, however, are of small geological importance, and their detailed study must be relegated to the science of Mineralogy. Fortunately it so happens that the number of minerals which play an important part as rock-formers is limited, and it is possible to draw up a short list which will suffice for our present needs. In later chapters the subject of the mineralogical and chemical composition of rocks will receive fuller treatment.

Common Rock-forming Minerals.—The great bulk of the rocks forming the accessible portion of the globe consist of the minerals included in the following list, associated in very variable proportions. Some rocks are homogeneous, consisting of one mineral species only, but most are heterogeneous, containing two or more.

List of Common Rock-forming Minerals.

Quartz.	Iron Pyrites.
Felspar group.	Calcite.
Mica group.	Dolomite.
Amphibole group.	Rock Salt.
Pyroxene group.	Gypsum.
Olivine.	Apatite.
Magnetite.	Garnet.

It will be observed that some of these are group-names, that is, general terms comprising several closely allied species which are separated by the systematic mineralogist. However, this separation can often only be made by refined methods, and for our present purpose these minute differences are unimportant, since the physical and chemical properties of the members of each group are very similar.

It must be clearly understood that the above list includes only a few of the commonly occurring minerals and might be very largely extended, but it is fairly representative and the student is recommended to make himself familiar with their chemical and physical characters, both by study of actual specimens and by the perusal of a small text-book of mineralogy.[1]

Different Classes of Rocks.—As we have already seen a rock may be defined as an aggregate of mineral particles ; but these aggregations are not all formed in the same way. Broadly speaking the rocks constituting the earth's crust may be divided into two great groups, the *igneous* and the *sedimentary* rocks. These two groups differ fundamentally in their mode of formation, since the igneous rocks are formed by consolidation from a state of fusion, while the sedimentary rocks are built up of the remains of pre-existing rocks, or else are deposited from solution by chemical or organic agencies. Corresponding to these differences of origin the whole structure and mode of occurrence of the two classes are essentially different, and it will be necessary to consider each class separately.

[1] An excellent book for the purpose is Dr. F. H. Hatch's *Mineralogy*, published by Whittaker and Co., London, 4th ed., 1912.

Intermediate in some respects between these two great divisions are the group of rocks known as *Pyroclastic*. These consist of igneous material, but have been formed in a manner more analogous to the sediments. They include the volcanic ashes and tuffs, and their consideration may be postponed till we come to consider the phenomena of vulcanicity in detail. Some writers make a fourth great class for the *Metamorphic* rocks, or those which have undergone such great alteration through heat or pressure, or both combined, that their original character is lost. However, these rocks were originally either igneous or sedimentary, and so the distinction is an artificial one.

The Igneous Rocks.—The igneous rocks as at present existing occur in two distinct forms, the extrusive or volcanic rocks, which have broken right through the crust and have been poured out at the

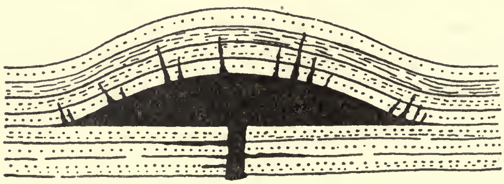


Fig. 1.—Laccolith.

surface as lava-flows from volcanoes, and the intrusive rocks, which have been injected into the crust, without reaching the surface. These two classes differ in form and structure, but have a common origin.

The forms assumed by extrusions of lava depend entirely on the laws governing the flow of liquids, and the chief factor in the case is the degree of viscosity in the molten lava at the time of extrusion; obviously a mobile liquid will flow further and spread itself out in a thinner sheet than a viscous one, other things being equal. Lava-flows therefore take the form of a sheet of greater or less extent, resting on what was then the surface of the ground, and all overlying rock must be newer in date. When a lava-flow occurs in this way in the middle of a succession of sedimentary rocks it is said to be interbedded with them, and is spoken of as a *contemporaneous* volcanic rock.

On the other hand, the intrusive rocks are those which have been injected into or between rock-masses which were already in existence, and the forms assumed by intrusions are capable of much greater variety than those of lava-flows. On the whole they are determined by the position of the planes of least resistance. Since they are often injected into sedimentary rocks their form depends on the structures of the latter.

The most common forms assumed by intrusions are *Bosses, Laccoliths, Bathyliths, Sheets* or *Sills, Dykes,* and *Volcanic Necks.*

Bosses are large masses of rock, often many miles in diameter, which appear to break through the strata without much reference to their structure and arrangement. Good examples are afforded by the Dartmoor granite, and other granite masses of the south-west of England. The original covering of rock has here been removed over a wide area, and the originally deep-seated igneous rock is well-exposed.

Laccoliths are intrusive masses which have arched up the overlying strata in the form of a dome, and they have usually something of the form of a bun or flat cake (Fig. 1). Laccoliths are not well developed in Britain, but are very well seen in some of the western States of America.

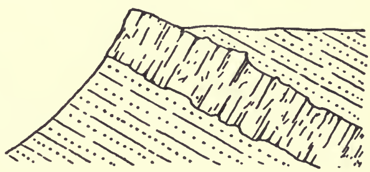


Fig. 2.—Intrusive Sill.

Sheets or *Sills* are intrusions which have forced their way along the stratification planes of sedimentary rocks, so that they lie parallel to the strata, and therefore might be mistaken for contemporaneous lava-flows (Fig. 2). They can, however, be distinguished by the fact that the overlying as well as the underlying rocks are altered or 'metamorphosed' by the heat of the intrusion; and a sill does not necessarily keep to the same stratification plane throughout its whole extent, but may cut across the strata, from one horizon to another. This is called Transgression. One of the best examples of such a sheet in Britain is the Great Whin Sill of the northern counties of England, which is intrusive into the Carboniferous rocks over an area of several thousand square miles, and is on the average about 100 feet thick, and transgresses for several hundreds of feet.

The term bathylith has recently come very widely into use to describe intrusions on an enormous scale, sometimes measurable by hundreds of miles, such as the great Coast Bathylith of British Columbia, which is 1,200 miles long by 150 miles wide at the surface, and of unknown extension in depth. Bathyliths are commonly intruded along the axis of a major fold of the earth's crust, in the form of an arch or anticline (see *post,* p. 19). Bathyliths may have an irregular upper surface with projections, or domes, which are often spoken of in America as 'cupolas.' Often also, as a result of denudation, isolated masses of the original covering rock are left, as it were, floating on the surface. It is possible that the granite masses of Cornwall and Devon are really cupolas on a bathylith, which is continuous below.

Dykes are vertical or highly inclined cracks in the crust which have been filled by an injection of igneous rock; they differ from sills in being as a rule more or less at right angles to the stratification, instead of parallel to it. Since igneous rocks are generally harder than the sedimentary rocks, dykes frequently stand up above the surface like walls, when the surrounding strata have been destroyed by weathering, and to this fact they owe their name. Dykes are very abundant in almost all parts of the world, and some very large ones exist in the north of England and the south of Scotland.

Closely allied to dykes are the smaller masses of igneous rock which are best described as veins. Their form is usually very similar to that of dykes, but more irregular, and they have no necessary relation to planes of stratification.

Volcanic Necks.—In many ancient volcanic regions we find masses of igneous rock of a more or less circular cross-section and therefore somewhat cylindrical in form (Fig. 3). These often break through the surrounding strata quite regardless of the structure and arrangement of the latter. They are masses of solidified lava filling up the pipes or vents of ancient volcanoes, and are often spoken of as *necks*.

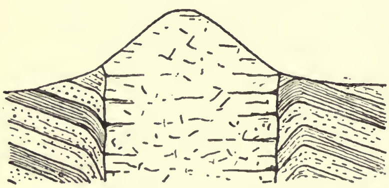


Fig. 3.—Volcanic Neck, filled with igneous rock.

Besides the foregoing there are masses of igneous rock of quite irregular forms which cannot strictly be referred to any of the above types. The forms of intrusions depend to a very large extent upon the structure of the rocks into which they have been injected, and these we must now proceed to consider.

The Sedimentary Rocks.—Since the sediments as a rule consist of particles which have been arranged under the influence of gravity, combined with water action, they frequently tend to occur in horizontal layers, which are often of wide extent. But since conditions are never uniform over the whole earth, or even over any considerable part of it, the lateral extension of a mass of sediment of any given composition must necessarily be limited. The result of this is that the thickness of the sediments laid down during a given time varies from place to place. A mass of material which has a uniform composition throughout is called a *bed*, and from the above considerations it appears that all such beds must really be lenticular in form, though these lenticles are often of enormous extent compared to their thickness.

It is convenient to use the term *strata* when speaking in general terms of the sedimentary rocks, which compose the greater part of the visible crust of the earth, and it is the province of the stratigraphical geologist to study the nature and order of succession of the varying layers or beds of which these strata are composed.

The character of the deposits formed naturally varies according to the conditions which prevail, and from a study of the nature of the sediments of any particular area we are able to draw conclusions as to the physical history of past ages in that area. It is unnecessary at present to enter into any details as to the minute structure of the sedimentary rocks, as this subject will be dealt with in a later section, but one or two examples may be given to show the relation between structure and origin. Suppose we find a rock consisting of a mass of well-rounded pebbles cemented together, in fact a consolidated gravel, it is obvious that at the time of its deposition the area was occupied either by a sea-beach or the bed of a river or lake, and so must have been either a land-surface, or close to a coast-line; similarly, a very fine-grained deposit containing only remains of marine animals indicates deep sea, and a thick bed of rock salt must have been formed by the drying up of a lake or inland sea. Thus by a study of the character and distribution of the sediments we are enabled to reconstruct the physical geography of the past.

Rock-structures.—The material of which the sedimentary rocks are composed is at first in a loose and incoherent condition, in the form of sand, mud, and so on. This applies to the deposits which are formed of material carried down from the land by water, and deposited in the sea, or in lakes and rivers, and also to such accumulations as desert sands, but exceptions occur in the case of some accumulations which are formed by chemical agencies, or by the vital activity of animals or plants. For the present, however, these exceptions may be disregarded, since the originally incoherent deposits form the majority. In course of time they lose this character, and become consolidated into hard masses, or rocks in the popular sense of the term. During these processes of consolidation various structures are impressed on the rocks, and these we must now proceed to consider briefly. Besides these original structures there are also structures of secondary origin, which are brought about by outside agencies after, and often long after, the original consolidation. Some of these structures are peculiar to the sediments, while others are common to both great classes of rocks, as will be pointed out in due course.

Stratification and Lamination.—If we examine any exposure of sedimentary rocks, on a sufficiently large scale, we shall see that the rock is not uniform from top to bottom, but is commonly marked out into bands or layers of varying appearance. These layers or *beds* are rendered visible by variations in physical character, such as differences of colour, hardness, and the like, and they usually indicate variations in composition also. This well-known feature of sedimentary rocks is expressed by the general term *stratification*. Since the rocks are usually laid down over fairly wide surfaces, these beds are at first horizontal; as a result of disturbing forces of later date they often lose their horizontality, and become inclined at various angles or even bent into folds. Nevertheless the original stratification still exists.

When a considerable thickness of sediment has been piled up, the lower layers are naturally subjected to pressure produced by the weight of the overlying mass, and the simplest effect of this pressure is to bring about consolidation of the lower part. This can be clearly seen in the case of the muddy sediments of the moderately deep sea. Among the ancient rocks we are able to trace every gradation from soft mud, through clays of varying degrees of plasticity, up to a hard rock, which shows no definite structure, and is called a mudstone. This change seems to depend to a very great extent on loss of water, since a very similar change can be brought about by slow drying of a clay by artificial means. It will be seen later on that drying is probably an important factor in producing rock-structures.

If such an originally homogeneous rock undergoes still greater pressures there will take place compression and rearrangement of particles. Rock particles are rarely of equal dimensions in all directions, and when subjected to pressure they tend to arrange themselves with their long axes perpendicular to the direction of pressure. In the case we are now considering this direction is the vertical one, since the force at work is the weight of the overlying strata. Consequently the longer axes of the particles lie in a horizontal position. If the rock was originally made up of flattened particles they will assume this position from the first. A rock built up in this way of particles all lying in one direction will split more easily in this direction than in any other, so that it will tend to split into layers parallel to the original bedding. This is known as *lamination*, and the thin layers are called laminæ. A muddy sediment possessing this structure gives rise to the easily fissile rock known as *shale*.

Lamination may also be brought about by the deposition of thin layers of varying character or by pauses in deposition. Let us consider the case of a mud-flat between tide-marks. During high tide a layer of mud or river silt may be deposited over it: when the tide ebbs, the surface is exposed to the drying effects of sun and wind, and becomes somewhat hardened on the surface: the next tide brings a fresh supply of mud, and so on. Thus a deposit is piled up consisting of successive layers with a slight want of coherence between them, and this also gives rise to planes of easy separation or lamination.

It will thus be seen that the difference between stratification and

PLATE I

Photo by H.M. Geological Survey.

BEDDING: ALTERNATING THIN BANDS OF LIMESTONE AND SLATE, UPPER DEVONIAN. PADSTOW, CORNWALL.

lamination is one of degree rather than of kind. *Stratification* or *bedding* (Plate I) is the division of the strata into larger bands of varying character, conspicuous from a distance; while lamination is a splitting up into thinner layers, only visible on close inspection. However, in geological writings the term 'bedding' is often used in a rather vague way to indicate the occurrence of evident stratification on almost any scale.

False-bedding.—This is a peculiar type of structure which is very characteristic of sandy rocks, and especially of those which have been formed in shallow water under the influence of strong currents. In this case the beds are not horizontal and continuous over large areas, but often steeply inclined in various directions within a small space (Plate II). Consequently examination of a small surface often seems to indicate highly inclined strata, while the bedding of the whole is really horizontal on a large scale, as will be seen if we regard only the top and the bottom of the bed.

Conformable and Unconformable Strata.—A series of beds which follow one another uninterruptedly in sequence, without any change

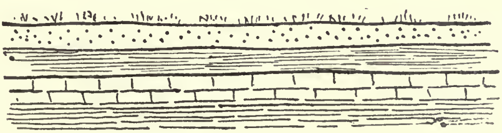


Fig. 4*a*.—Horizontal Strata in Conformable Series.

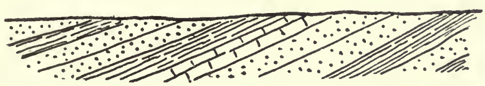


Fig. 4*b*.—Inclined Strata in Conformable Series.

in their general parallel arrangement, is said to be *conformable* (Fig. 4*a*). In some districts great thicknesses of strata occur, often for several thousand feet, without any break. This indicates the prevalence of uniform conditions for a long space of time, so that deposition of sediments has gone on uninterruptedly. Such strata have often been moved from their original position, and uplifted and inclined, without their conformability being affected. Suppose, however, that a set of marine sediments has been uplifted to form dry land; they are brought within the reach of the agents of destruction and undergo *denudation* (Fig. 4*b*). If these denuded strata are again brought below sea-level a fresh series of sediments will be laid down on the top of them. This second series will not necessarily be parallel to the first, and in any case there will be a gap in the succession. If the first series has been inclined as well as uplifted, the second set will rest on its worn and denuded edges, and the bedding of the two sets will lie at different angles. This phenomenon is known as *unconformability*, and the two sets of strata are said to be *unconformable* (Fig. 5*a* and Plate III (i)). Since the sedimentary rocks are as a rule laid down in

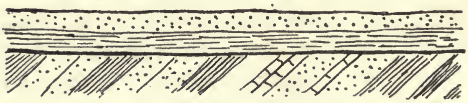


FIG. 5*a*.—UNCONFORMITY.

more or less basin-shaped areas, with gently sloping sides, such as lakes or the sea, it is evident that each successive bed will extend further in a horizontal direction than the one below it. This is called *overlap* (Fig. 5*b*).

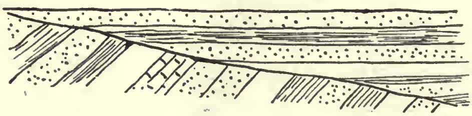


FIG. 5*b*.—UNCONFORMITY WITH OVERLAP.

Dip and Strike.—When a bed is inclined its surface makes a certain angle with the horizontal plane, and this angle is called the *dip* of the bed. It is measured in degrees from the horizontal, and the direction of the dip is referred to the points of the compass. Thus the surface of a certain bed might be inclined downwards towards the north-east, and the greatest angle which could be measured between its surface and the horizontal plane might be 35°. This is expressed by saying that the bed dips north-east at 35°. The angle of slope measured in any other direction would obviously be less than the true dip. Thus it appears that dip may be described as the greatest angle which can be made with the horizontal plane by a line lying in the bedding plane. This would be the course pursued by a drop of water running freely down the surface of the bed, since it is the steepest possible slope, and therefore the line of least resistance.

A horizontal line at right angles to the direction of dip is called the *Strike*. Thus, in the case before supposed, the strike of the beds would run north-west and south-east.

If we imagine a piece of absolutely level ground composed of a series of inclined strata, the surface of the ground will consist of the

PLATE II

C. A. Defieux, photo.

FALSE BEDDING IN TRIASSIC SANDSTONE, CHESHIRE.

truncated edges of the beds. The space occupied on the ground by any bed is called its *Outcrop*, and the direction and width of this outcrop will evidently depend primarily on the dip. If the beds are horizontal the ground will be composed of the upper surface of the uppermost bed only, and the width of the outcrop is infinite. If the beds are vertical the width of the outcrop is the true thickness of the bed; in any

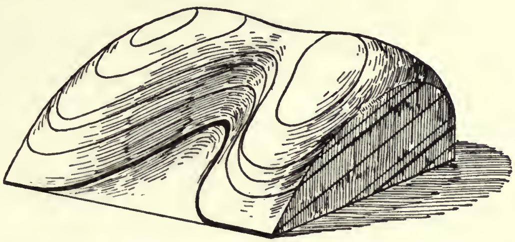


FIG. 6.—BEDS DIPPING AT A LESSER ANGLE THAN THE SLOPE OF THE VALLEY FLOOR; V OUTCROPS UP-STREAM.

intermediate position the width will depend upon the angle of inclination, i.e. the dip. Thus the outcrop of uniformly dipping beds on level ground will be a series of parallel bands of varying width. Here the strike and the outcrop obviously coincide.

If, however, the ground surface is undulating the matter is less simple. Vertical beds must in all cases crop out as straight lines, but

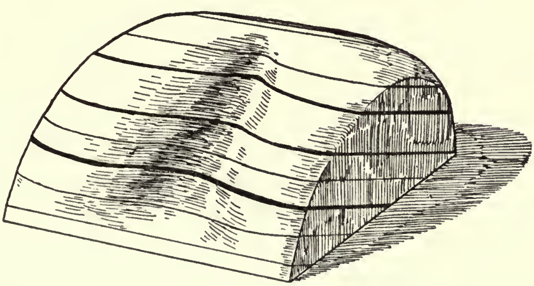


FIG. 7.—BEDS DIPPING AGAINST THE SLOPE OF THE VALLEY; V OUTCROPS UP-STREAM.

inclined beds cannot do so. Their outcrops will follow sinuous courses, and the less the angle of dip the more sinuous their course will be (Figs. 6, 7 and 8). Finally, if the beds are horizontal, their outcrops will be parallel to the contour-lines, that is, the lines indicating equal heights above sea-level. This subject of dip, strike and outcrop is of the utmost importance in geological mapping, but cannot here be pursued further; for full details reference must be made to some text-book of Field Geology.[1]

Divisional Planes, Joints.—So far we have spoken of rocks as if they were continuous structures, forming one solid mass of indefinite extent, but this is not the case. Rocks are affected by planes of division of various kinds, which break them up into more or less well-defined masses. A brief reference has indeed been made to stratification and lamination, which are to some extent divisional planes, but frequently without actual discontinuity. In very many cases, however, we find that a rock-bed consists of separate blocks, often with considerable spaces between them. These planes of division are known as *Joints* (Plate III (ii)). It is to be noted that joints are found in the igneous as well as in the sedimentary rocks. Their origin in both classes appears to be very much the same. Most commonly, perhaps, they arise from shrinkage after formation: in the igneous rocks during

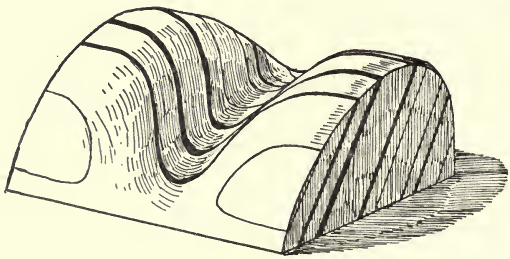


Fig. 8.—Beds dipping down the Valley at a Greater Angle than the Valley Slope; V Outcrops down-stream.

[Figs. 6, 7, 8 are drawn from Sopwith's models.]

cooling, and in the sediments during drying. In other cases joints are due to strains set up by movements of the crust, as will be noticed further on. A good example of jointing in igneous rocks is afforded by the well-known columnar structure of the basaltic lavas of the Giant's Causeway and Fingal's Cave. A much less perfect system of joints is almost universal in igneous rocks, and there is a general tendency to split up into hexagonal columns or cuboidal forms. Jointing may be seen in almost any quarry, and it will often be noticed that the principal joints have a tendency to arrange themselves in two or three sets, more or less at right angles. In sedimentary rocks one set is usually along the bedding planes, while the other two are usually parallel to the dip and strike respectively. These are called dip-joints and strike-joints. The smaller joints are often more irregular

[1] See also Appendix at the end of the present Chapter.

S. H. Reynolds, photo.

(I) CARBONIFEROUS LIMESTONE RESTING UNCONFORMABLY ON LUDLOW SLATES. NEAR SETTLE, YORKSHIRE.

R. H. Rastall, photo.

(II) JOINTS IN IGNEOUS ROCK. LITTLE KNOTT CUMBERLAND.

in their distribution. In chalk-pits in Cambridgeshire and elsewhere it can often be seen that the rock is divided up into irregular blocks by peculiar curved joints, and there is often evidence of differential movement along them. The origin of these curved joints is somewhat doubtful.

Folding.—We have seen that the bedding planes of the stratified rocks do not always remain in their original horizontal position. As a result of the various movements of the earth's crust, to be hereafter described, they become inclined in various directions and at various angles (cp. Plate VI (ii)). But besides this simple tilting movement

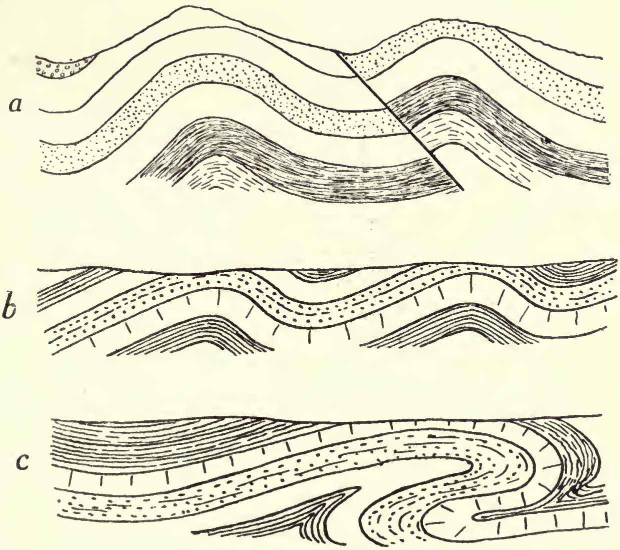


Fig. 9.—Types of Folding.

a, Symmetrical folds; *b*, Asymmetrical fold; *c*, Recumbent fold.

they often undergo bending or warping: this process is conveniently described as *folding.* A special nomenclature is in use to describe the different types of *folds* which may be produced, and the different parts of an individual fold. The simplest case is when the strata are simply lifted up in the form of an arch; this is called an *anticline*, and the beds dip on both sides away from the central line, the *axis* of the fold. The corresponding structure when the beds dip towards the axis is a *syncline.* *a*, Fig. 9, shows a series of beds folded into a succession of anticlines and synclines. In this case the slopes are similar on both sides of the axis, and the folds are said to be *symmetrical.* Since, however, folds are most commonly the result of a thrusting movement of the crust, acting in a tangential direction, one side of the fold is usually steeper than the other, as shown at *b*, Fig. 9. Such a fold is said to be *asymmetrical* (cp. Plate VII (i)).

The various parts composing such a wave-like fold are designated *limbs*, and three regions are usually distinguished, viz. arch limb, trough limb, and middle limb or septum, as indicated in Fig. 10. Folds of the type so far described are normal. But if the lateral thrust is still more powerful, the fold may be more or less overturned on the side away from the stronger pressure, forming what is known as an *overfold* (see *c*, Fig. 9). In this case it is evident that a vertical shaft sunk from the surface may pass through the same bed three times, and in one part of the shaft the succession will occur in reverse order, that is to say the beds in the middle limb are *inverted*. Such inversions are very common in many mountainous regions, which are usually built up of a complex series of folds.

If the elevation takes place around a point, so that the beds dip away from the centre in all directions, the resulting structure is called a *dome;* while if the dips are all inwards towards a centre, it is a *basin*. Domes and basins are not usually absolutely circular, but oval, and may be regarded as very short anticlines and synclines. It is to be noted also that folds are never of indefinite length, but eventually die out, so that in one sense they are only very elongated domes and basins. The difference is therefore only one of degree.

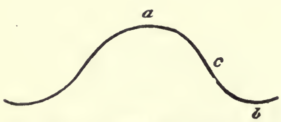


FIG. 10.—SYMMETRICAL FOLD.
a, Arch limb ; *b*, Trough Limb ; *c*, Middle limb, or septum.

So far we have tacitly assumed that the axes of folding are horizontal, but this is by no means always the case. The axes are frequently inclined, and are then said to *pitch*. A fold whose axis was inclined downwards towards the south-east would be said to pitch to the south-east, and the angle of pitch could be expressed in degrees, as in the case of dip.

One of the simplest cases of folding is the type known as *monoclinal*. This is often represented as a simple elevation or depression of one part of a region in relation to the other, with a curved portion between them ; but it is doubtful if such a structure really exists. Monoclinal folds are in nearly all cases very asymmetrical anticlines with much elongated arch and trough limbs and a very short, steep septum. Unfortunately, the term monocline is also used by some American authors to describe a series of inclined beds all dipping in the same direction.

By some authors the term *recumbent anticline* is used to describe an overfold. A series of overfolds arranged in such a manner that both limbs dip in the same direction is called *isoclinal* folding. Consideration

PLATE IV

Photo by H. M. Geological Survey.

PUCKERED SLATE, SHOWING STRAIN-SLIP CLEAVAGE: THE TRUE CLEAVAGE IS NOT RECOGNISABLE. WATERGATE BAY, CORNWALL.

PLATE V

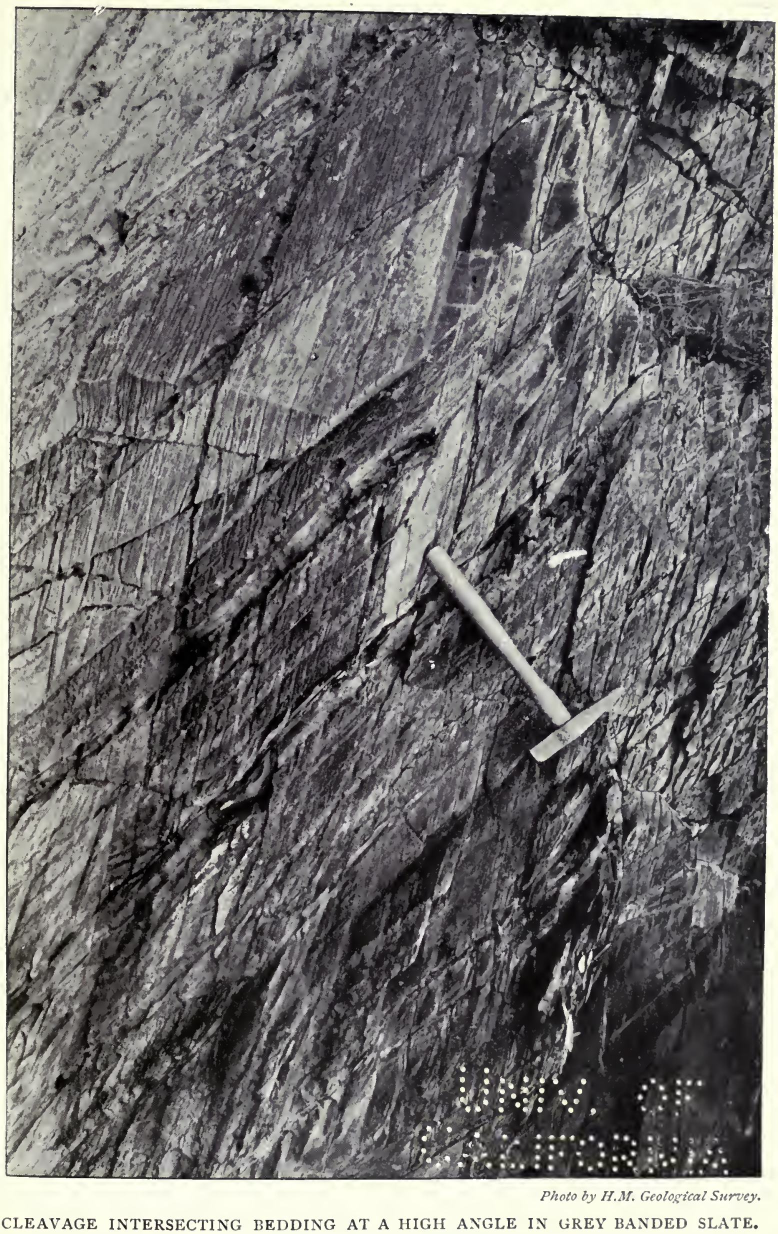


Photo by H.M. Geological Survey.

CLEAVAGE INTERSECTING BEDDING AT A HIGH ANGLE IN GREY BANDED SLATE.
WADEBRIDGE, CORNWALL.

of more complex arrangements of folds may conveniently be deferred till we come to treat of earth-movements in general, as they are most conveniently illustrated by the study of special examples.

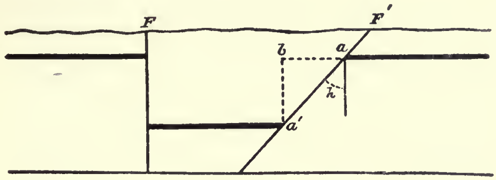


FIG. 11.—DIAGRAM OF FAULTS.

F, Vertical fault; *F′*, Normal fault; *baa′*, the dip; *h*, the hade; *ab*, the heave or want; *a′b*, the throw.

Faulting.—Rocks do not possess much elasticity, and under the influence of the strains set up by crust-movements fractures are frequently produced. These fractures are known as *Faults*. Thus it will be seen that faulting is closely connected with folding. The tension of

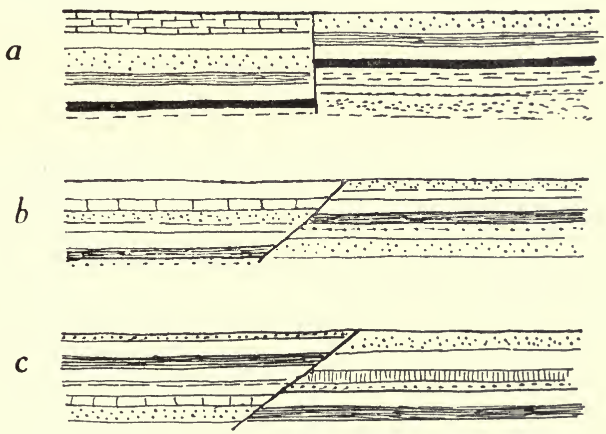


FIG. 12.—DIFFERENT TYPES OF FAULTS.

a, Normal fault, downthrow to left, fissure vertical; *b*, Normal fault with inclined fissure, hading to the left; *c*, Reversed fault, upthrow to left, hading to left.

the strata during folding frequently passes the limit of elasticity, and the rocks break along the line of least resistance. As a result of this fracture there will occur more or less differential movement of the rocks on the two sides of the fissure, and the amount of relative displacement may be measured. The fault-fissure may be either vertical or inclined :

if inclined, the amount of inclination measured from the vertical is called the *hade* of the fault, and it is expressed in degrees. The amount of vertical displacement is the *throw* of the fault, and the side which is relatively raised is called the *upthrow* side; the other is the *downthrow* side. These relations are indicated in the diagram (Fig. 12). It is

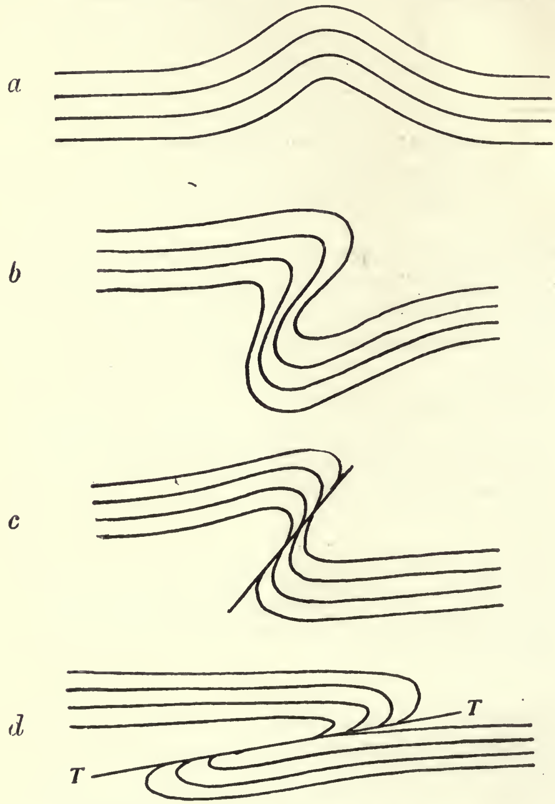


FIG. 13.—FORMATION OF AN OVERTHRUST.

a, Simple arching; *b*, Becoming an overfold; *c*, Septum replaced by a fault; *d*, Upper strata carried over the lower along the thrust-plane *T T*.

evidently immaterial in this case whether the strata on the right have moved up, or those on the left down: we are only concerned with relative displacement.

In dealing with inclined faults, however, there is one important distinction to be observed: at *b*, Fig. 12, is shown a fault inclined or hading to the left; the downthrow also is to the left. This is called a *normal*

PLATE VI

Photo by H.M. Geologcal Survey.

(I) FOLIATED GNEISS. NEAR LAXFORD BRIDGE, SUTHERLAND.

Photo by H.M. Geological Survey.

(II) VERTICAL STRATA IN UPPER OLD RED SANDSTONE. SANDTOP BAY, CALDY ISLAND, PEMBROKESHIRE.

fault. c, Fig. 12, shows a fault dipping in the same direction, while the upthrow is to the left, so that one part of the bed lies vertically above the other part for a certain distance. This is called a *reversed fault.* Obviously, in the case of a reversed fault a vertical shaft sunk between certain points will pass through the same bed twice, while in a normal fault it cannot do so, and may even miss it entirely.

FIG. 14.—THRUST-PLANE AMONG THE MOUNTAINS SOUTH OF THE LAKE OF WALLENSTADT. (After Professor Rothpletz.)

1, Trias; 2, Lias; 3, Cretaceous; 4, Tertiary. *T*, *T*, Great thrust plane; *b*, Normal fault.

Since the septum of a fold is the weakest part of it, faults often tend to be formed here, and in particular overfolds often pass over into reversed faults, as shown in the figure, and if the thrusting movement continues the two ends of the same bed may eventually be separated by a considerable distance. Obviously also the hade of the fault may become very great, that is to say it may be inclined to the horizon at a very low angle; such reversed faults with an inclination approaching the horizontal and a large displacement are usually distinguished as *thrust-planes*. By them one part of a set of beds is sometimes carried over another part for many miles (see *d*, Fig. 13). These *over-thrusts* often occur on a large scale in mountain chains, which have been formed by powerful folding (Fig. 14).

Faults vary very much in size and in arrangement: the throw may be anything from an inch or two to thousands of feet, and they may

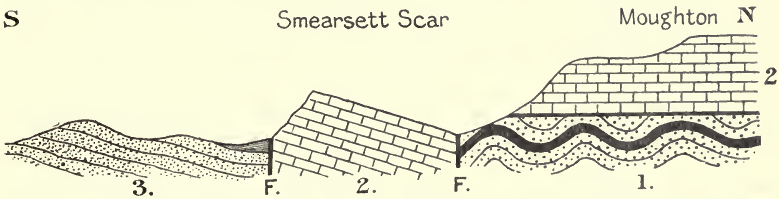


FIG. 15.—GENERALISED SECTION ACROSS THE CRAVEN FAULTS, WEST YORKSHIRE, SH WING HOW THE CARBONIFEROUS STRATA ARE SUCCESSIVELY FAULTED DOWN TOWARDS THE SOUTH.

The total throw of the two faults is about 1,500 feet.

1, Silurian; 2, Carboniferous Limestone, Lower Carboniferous; 3, Millstone Grit, Upper Carboniferous.

occur either singly or in groups. Very often several parallel faults occur near together, running in the same general direction. It is clear that if a series of parallel faults affect inclined strata the outcrop of any particular bed may be repeated several times, as shown in Fig. 16.

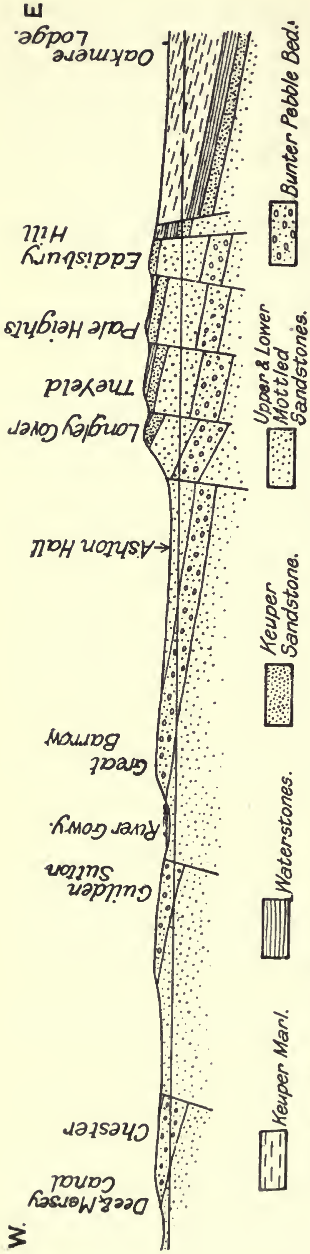


Fig. 16.—Section from Chester to Delamere Forest, showing Repetition of Triassic Strata by Faulting.
Total length about ten miles. Vertical scale exaggerated.

Faults often produce notable effects on the topography of a region where they occur by bringing together strata of very different resistance to weathering, so that the harder rock may stand up like a wall, forming what is known as a fault-scarp. A good example of this is seen in Giggleswick Scar, in West Yorkshire, where a cliff of hard limestone north of the Craven fault stands up above the lower ground formed by the softer beds on the south side (see Fig. 15).

Cleavage.—We have already seen how as a result of the pressure of overlying rocks there may be set up in fine-grained sediments a fissile structure known as lamination. A somewhat similar structure, but much more highly developed, frequently results from the intense pressures set up during earth-movements. Cleavage differs from lamination, however, in one important particular: lamination is necessarily parallel to the original bedding, while cleavage may make any angle with the bedding, and is very commonly more or less at right angles to it. Cleavage is a property of splitting along planes lying in a definite direction, and this direction is always perpendicular to the pressure.

As in the case of lamination particles tend to arrange themselves with their long axes perpendicular to the pressure, but besides this there is always a large amount of actual deformation and shearing, accompanied by recrystallisation, so that cleavage involves a good deal of mineralogical change as well as a merely mechanical one.

For the proper development of cleavage it is probable that a considerable load of overlying rock is necessary to prevent folding and flowing of material, so that the action is probably a deep-seated one. Cleavage takes place most readily in fine-grained sediments, such as clay and shale, and also in fine volcanic ashes. The resulting well-cleaved rock is called a *slate*. Sometimes the original bedding is completely obliterated, but generally it can be distinguished by differences of colour and texture in successive bands (Plate V). This is well shown by the green stripes which are so common in the purple roofing-slates of Carnarvonshire, and usually make a high angle with the cleavage planes. Rocks may be cleaved in more than one direction as a result of successive pressures, and will then tend to break up into various regular solid figures, instead of thin slabs.

Coarse-textured rocks, such as sandstones, do not readily undergo cleavage, and sometimes slates enclose grit bands which have resisted cleavage, but have been folded and contorted in various ways.

Foliation.—Closely allied to cleavage is the structure known as *foliation*. This consists essentially of a parallel arrangement of the minerals of the rocks, and this parallel arrangement often induces a tendency to split in definite directions; however, this does not amount to true cleavage, as the fracture is usually imperfect and irregular. Foliation is a result of very high pressures produced by earth-movements, and it is always accompanied by a more or less complete recrystallisation of the minerals, or formation of new minerals. It affects not only fine-textured sediments, like cleavage, but also coarse-grained rocks of all kinds, both sedimentary and igneous. The rock types produced by this process are known collectively as gneisses and schists; the difference between the two classes is not very definite, but on the whole the gneisses are coarse-grained and look like crushed igneous rocks (Plate VI (i)), while the schists are finer in texture, approaching slates, and in many cases probably derived from sediments. The term 'foliation' is now also used to describe parallel structures in igneous rocks, due to flow during cooling. This is called primary foliation.

CHAPTER II

DENUDATION

Introductory.—It is a fact scarcely needing extended demonstration that the surface of the land is undergoing a constant process of destruction. Every shower of rain can be seen to carry loose material to a lower level, and in flood-time rivers are rendered turbid by the amount of solid matter which they bear along in suspension. At the foot of steep slopes and precipices in mountain regions may be seen piles of angular rock-fragments which have obviously fallen from above, and the beds of the streams are full of subangular and rounded pebbles derived from higher levels. In desert regions an unfailing supply of sand is whirled along by the wind, and fills up the hollows : it can only be formed by the disintegration of the rocks of other parts of the desert itself. Examples might be multiplied indefinitely to show that the land-surfaces of the globe are undergoing a constant process of loss. Since the destruction of the present land affords the material from which modern deposits are being built up, to be eventually in their turn raised into land, it is logical to begin our consideration of geological processes with a discussion of the manner of origin of the raw material at the present day, and the light which this casts on the processes at work in the past. We shall therefore assume the existence of the earth in its present condition, and we shall begin with a study of the processes of destruction at present in operation, which are comprised under the general term of *denudation.*

Climate and Denudation.—Since denudation is chiefly brought about, either directly or indirectly, by atmospheric agencies, the character and extent of the denudation in any given district are to a large degree controlled by the climatic conditions which prevail in that district. The different agents of denudation will be considered in detail in subsequent sections, but it may be said here that the most important of them are gravity, water, ice, wind and, in a less degree, plants and animals. Of these, gravity is unaffected by climate, but the rest are directly dependent on it.

From this point of view the land-surfaces of the globe may be classi-

F. H. Hatch, photo.

(I) SHARP ANTICLINE: ONE LIMB STEEPER THAN THE OTHER. NKOMO, NATAL.

Photo by H.M. Geological Survey.

(II) TYPICAL WEATHERING OF GRANITE. CARN BREA, REDRUTH, CORNWALL.

fied under four principal types, which are distributed in zones parallel to the equator, so that denudation is to a certain extent a question of latitude. These zones are as follows: first, there is the equatorial belt, with high temperature and heavy rainfall and consequent luxuriant vegetation. On either side of this comes a belt of high temperature and small rainfall, giving rise to more or less clearly developed desert conditions, with conspicuous absence of plants and animals. Outside of this comes in each hemisphere the temperate zone, with a cool climate, abundant rainfall, and a thick covering of vegetation. Lastly, in the arctic and antarctic regions there is very low temperature, so that most of the precipitation is in the solid form, as snow: running water is rare or absent, and so far as vegetation is concerned the conditions are those of a dry climate: there is no vegetation, and animal life is scarce.

These four types may be summarised as follows:—

(*a*) Equatorial belt, hot and damp.
(*b*) Desert belts, hot and dry.
(*c*) Temperate belts, cool and damp.
(*d*) Arctic belts, cold and dry.

The denudation which occurs in each of these climatic zones possesses special distinguishing characteristics, according to which of the agents above enumerated is the dominant one. These will be dealt with later in detail. Marine denudation is also an important subject, and requires separate treatment. It is not much affected by climate, except in the arctic zones, where its effects are complicated by the presence of sea-ice.

Denudation.—The process of denudation is a threefold one: it is necessary first to consider the actual loosening and breaking up of the material; secondly, the means by which the loosened material is removed from its original situation; and, thirdly, the geological work which it does during transit to its next comparatively permanent resting-place. These processes are now distinguished as Weathering, Transport and Corrasion respectively: the sum-total of their effects is comprised under the general term Erosion.

(1) Weathering

Under this heading, as above stated, are to be included all the processes which bring about the actual disintegration of the rocks, and preparation of the material for the action of transporting agents (cp. Plate VII (ii)). Weathering is partly of the nature of chemical action, although many of the processes are to be regarded as mainly physical or mechanical. Rocks have already been defined as aggregates of particles, either of minerals or of amorphous matter, and it has also been pointed out that minerals are compounds having a definite crystalline form and a more or less definite chemical composition. Some volcanic rocks consist wholly or in part of an amorphous substance of variable composition, usually known as glass, but the majority are composed of crystalline minerals. Some rocks consist wholly of mineral particles, crystals or grains, while others consist in part of mineral particles and in part of some cementing material, which holds the grains together into a coherent mass. The facility with which a rock can be broken up into its component particles will evidently depend on the nature of this cement, other things being equal. Most of the sedimentary rocks are held together by a cement which is somewhat easily broken up, so that they easily undergo mechanical weathering, and many of them are distinctly soft rocks.

The igneous rocks, on the other hand, have crystallised from the molten state, and they are held together by the cohesion of their crystals alone : in their original form they never possess a soft cement, and may therefore be regarded as hard rocks. This is true of the fresh, unaltered rocks : some are much more susceptible to weathering than others, so that igneous rocks do not always resist denudation better than sediments.

Chemical Weathering.—The minerals composing rocks may be regarded as chemical compounds, whose composition and physical properties depend on the conditions under which they were formed. If these conditions remain unchanged, the minerals also will remain unaltered, that is to say they are stable. But in the course of their existence rocks are subjected to great changes, so that some or all of their minerals may become unstable under the new conditions, and will themselves undergo alteration. The general result of these processes is to break up the rock : the minerals are decomposed, and their constituents are set free to enter into new combinations, either among themselves or with substances brought in from outside. Thus a great variety of chemical reactions are set up and new compounds are formed.

Chemical Action of the Atmosphere.—The ordinary constituents of the atmosphere are nitrogen, oxygen, carbon dioxide and water-vapour, with a very small proportion of nitric acid and ammonia. Nitrogen is a very inert substance and plays no part in weathering, and the amount of nitrogen compounds is so small that they also may be disregarded. The carbon dioxide in the air of the open country generally amounts to about 3 parts in 10,000, though it is somewhat variable. Small as this amount may seem it is of great importance, and it is clear that carbon dioxide dissolved in water plays an important part in chemical weathering. This will be discussed more fully when dealing with the effects of water on rocks and minerals.

Many of the processes of weathering depend on oxidation. Here again, however, the action is much intensified by the presence of moisture and carbon dioxide, and many processes of oxidation cannot proceed at all if the air is perfectly dry. A familiar example is the rusting of iron and steel in damp air, and the same applies to innumerable other chemical reactions.

The atmosphere contains a large and variable proportion of aqueous vapour, and this is of the utmost geological importance. There is constant transfer of water in the form of vapour from the hydrosphere to the atmosphere, and back again, through and over the lithosphere to the hydrosphere as rain and snow, so that all the water of the land has at one time or another existed in the form of vapour in the air.

It appears, then, that it is difficult, if not impossible, to separate the effects of the different gaseous constituents of the atmosphere from the effects of water in the liquid state within the rocks themselves, since these constituents, and especially oxygen and carbon dioxide, are most active when dissolved in water.

Physical Action of the Atmosphere.—Besides the chemical processes briefly enumerated above, there are certain important physical weathering agents which must be ascribed to atmospheric causes. It is well known that most ordinary solid substances expand when heated and contract on cooling. Now rocks are not homogeneous, but are aggregates of different substances which behave differently in this respect. They will not act as a whole, as a homogeneous substance would do, but each individual crystal or grain will expand or contract according to its nature. As a consequence of heating and cooling, great strains are set up, and fractures of all degrees of magnitude may take place. In tropical countries, and especially in dry regions where the sky is clear and radiation is uninterrupted, the difference between day and night temperatures is often very great, and the fall of temperature after sunset is rapid. In such regions disintegration of rocks by this means occurs on a very large scale, and gives rise to the great piles of angular scree material which are so common at the foot of mountain slopes in desert regions. In temperate climates the same process undoubtedly occurs on an appropriate scale, though its effects are usually masked by the effects due to the expansion of water in freezing.

Chemical Action of Water.—Passing on now to consider water as a weathering agent, it will be found that its effects are manifold. It has already been pointed out how the chemical activity of the gases of the atmosphere is increased by the presence of water, but besides this water has many effects peculiar to itself, and it is undoubtedly the most important agent of weathering.

Most of the ordinary constituents of rocks are more or less soluble in pure water, but in nearly all cases their solubility is so small as to be negligible. It is only exceptional deposits, such as beds of common salt, which are freely soluble. If water by any means comes in contact with such a bed, important results may follow. Calcium carbonate and silica are also to some extent soluble in pure water. If, however, the water is not pure, and especially if it contains acids, its solvent power is largely increased. The most important of these acids is carbonic acid or dissolved carbon dioxide. The origin of most cases of chemical weathering can be traced to the action of water containing dissolved carbon dioxide or oxygen, or both. These set up secondary reactions, so that the whole becomes very complex, since it involves various processes of solution, hydration and oxidation. In the case of the igneous rocks the felspars are decomposed to mica, calcite and kaolin ; the ferro-magnesian minerals give rise to hydrated compounds such as the chlorite group and serpentine, or various carbonates ; while the iron ores are oxidized and hydrated. The quartz is not affected, and is set free to form sand grains. The sedimentary rocks also are attacked, calcareous and ferruginous cements are dissolved, and the mineral grains are set free : iron pyrites and other sulphur compounds are oxidized to sulphuric acid, and a whole series of similar changes is set up.

In the case of the calcareous rocks also the solvent action of water is very important ; the solubility of calcium carbonate is much increased by the presence of dissolved carbon dioxide, while pure water has little effect. Water percolating through the rocks of limestone districts and along their fissures dissolves away the rock often to a large extent, and may result in the formation of caverns, like those of the Mendips, Derbyshire, or West Yorkshire, or the gigantic caves of Styria and Kentucky. These caverns are the courses of underground rivers, and have in most cases been hollowed out by the solvent action of the water of the rivers, which worked along joints previously existing in the rocks.

Oxidation is of considerable importance as a weathering agent ; its effects are most conspicuous on the compounds of iron, which are so widely distributed and so abundant in the rocks. In most of the igneous rocks a large part of the iron exists in combination in the ferrous state, and when the complex molecules of the silicates are broken up this ferrous iron readily passes into the ferric condition. To this process of oxidation of iron is due the yellow or brown crust which is so common on weathered surfaces of rocks which when fresh are black, grey, green or blue in colour; and, in fact, the prevailing colour of almost all rocks depends on the state of oxidation of the iron which they contain. Almost all soils show some tint of yellow, brown or red, whatever may have been the original colour of the rocks from which they were derived. Here also the change of colour is due to oxidation.

The reverse process of deoxidation or reduction is apparently not of much geological importance, and cannot be expected to occur frequently on a large scale, since under the prevailing conditions of the earth's surface the highly oxidized compounds are the more stable. The most common reducing agent in nature is organic matter, and it is to be noted that strata stained red by ferric iron often show green or white spots, which are doubtless due to local reduction of the iron compounds to the ferrous state during decomposition of the organic matter originally entombed in them. According to Prof. J. Walther, the prevailing deep-red colour of desert deposits, both ancient and modern, is due to the absence of any appreciable quantity of animal or vegetable matter, which could bring about reduction.

Water and Ice as Mechanical Agents.—The mechanical action of water and ice belongs rather to the provinces of transport and corrasion than to weathering, but there is one process which strictly appertains to this part of the subject. As is well known, water differs from most other common substances in that it expands in passing to the solid state, and this expansion is large, amounting roughly to 10 per cent. The expansion also exerts enormous pressure, so that when water freezes within the cavities and interstices of a rock great strains are set up, and fragments may be broken off, or the rock shattered to a considerable depth. This agency is of great importance in cold climates and in high mountain districts, and the great accumulations of rock débris which occur in such regions are chiefly formed in this way. Frost also plays an important part in loosening surface accumulations and rendering them more easily acted on by agents of transport. This effect can be easily seen on the surface of roads and ploughed fields after a thaw. The water in the soil expands on freezing and increases the distance between the solid particles: when the ice melts and the water returns to its original volume, or is removed altogether by evaporation, the soil is left in a spongy state, so that it is easily carried away by running water.

Action of Plants and Animals.—Besides the inorganic agents of weathering described above, a good deal of rock-destruction can be traced to the vital activity of plants and animals, especially the former. The roots of plants secrete acid juices which enable them to decompose the minerals of the soils and rocks, into which they often penetrate for long distances. They have also a considerable mechanical efficiency in widening existing fissures and facilitating the entrance of water and air. A thick covering of vegetation has also a certain conservative effect in protecting the soil from removal. As a consequence of this the surface of the ground in temperate, and still more in equatorial, regions is usually covered by a thick coating of disintegrated material, formed by weathering *in situ.*

Even such lowly organised plants as mosses and lichens play their part in weathering, since they help to retain moisture on rock surfaces, and their juices also have a corrosive effect. Tufts of moss and lichens are frequently found to lie in little hollows which have been formed in this way, and these are true rock-basins on a small scale.

Recent researches have shown that bacteria exert an important influence in the decomposition of certain types of rock, and in particular of calcareous rocks, which are acted on by the nitrous and nitric acids formed by the nitrifying bacteria. The soluble calcium nitrate thus produced is taken up by higher plants. It has also been suggested that the formation of laterite and other red argillaceous deposits from decomposing igneous rocks may be partly or wholly due to bacteria.

The geological activity of animals lies rather in the direction of deposition than of denudation. However, Darwin has clearly shown the important work of earthworms in bringing to the surface vast quantities of finely divided soil, which has been passed through their alimentary canals, and is in a state rendering it liable to be easily carried away by running water. Other burrowing animals, such as rabbits and moles, have also a certain geological effect.

Surface Accumulations and Soils.—The ultimate result of all these processes, where not modified by transport, is the formation of a covering of loose material of varying thickness above the solid rocks of the land. However, not all surface accumulations come under this category, since a very large proportion of them have undergone more or less transport from their original situation, and some, such as river alluvium and glacial deposits, consist of material which is now at a long distance from its point of origin. These will be dealt with fully in the chapter on Terrestrial Deposits. It is a fact, however, that large regions of the earth are covered with loose material which is actually *in situ.* Reference has already been made to the great blankets of weathered rock in tropical regions, and something of the same sort occurs in temperate climates. It is a commonplace that where not masked by glacial drift the character of the soil depends on that of the underlying rock, and the deep, rich soil of the Severn valley, derived from the decay of the Old Red Sandstone, differs greatly from the poor, thin, whitish or grey soil of the Chalk, and this again from the sparse sandy covering of the Yorkshire moors, lying on sandstones and shales. These examples, chosen at random, are sufficient to show that the original character of the rock persists sufficiently to make itself prominent in the nature of the soils. The existence of a covering of residual soil is in itself a proof that in the area in question weathering is in excess of transport, while bare rock-surfaces, especially when highly inclined or vertical, show that all loose material is carried off as fast as it is formed.

Influence of Latitude on Weathering.—Weathering is not a uniform process all over the world, its nature and extent being largely controlled by climatic conditions. From this point of view four types of climate may be recognised, as follows,—first, the damp equatorial belt; second, the desert belts; third, the temperate zones; and fourth, the arctic regions. Hence it appears that the principal factor in determining the character of the weathering in any given area is latitude. Each of the regions enumerated above presents peculiarities of its own, some of which must now be considered.

Weathering in Equatorial Regions.—Where the rainfall is heavy and the temperature high solution and chemical processes in general are active, and the effects due to organic agencies are well marked, while the action of frost is excluded. The chemical changes are often different from those which take place in cooler latitudes. The decomposition of silicates is more complete, and the silica is often entirely removed in solution. A characteristic product is laterite, which takes the place to a large extent of the clay of more northern regions. Laterite consists largely of hydrated oxides of aluminium and iron, while clay is a hydrated silicate of aluminium.

Weathering in Desert Regions.—In those parts of the world which are specially characterised by a dry climate and consequent absence of vegetation, that is to say in deserts, peculiar conditions prevail, and the character of the weathering differs a good deal from what is found elsewhere. True deserts chiefly occur in more or less continuous zones on either side of the equatorial belt, and in the majority of cases the temperature is high, at least during the day, while the nights are often cool or even cold. Consequently the daily range of temperature is often very great, so that here the effects of alternate expansion and contraction have full play.

The processes of weathering in deserts may be briefly summarised as follows: [1] ordinary rainfal is practically absent, so that there is no solvent action of the ordinary kind, but there is always a certain amount of water held in the rocks by capillary attraction. This is probably derived from the rare but violent rain-storms and cloud-bursts which occur even in the driest regions. Since the sun's heat is very strong and the air dry, this capillary water is drawn out and brings with it to the surface the soluble salts of sodium, magnesium, &c., with which many desert deposits are saturated. Chemical reactions occur between these hot strong solutions and the constituents of the rocks, so that the latter are decomposed from within outwards. This process leads

[1] Walther, *Das Gesetz der Wüstenbildung*, Berlin, 1900, chap. iii.

to cementing and solidification of some loose sediments, and colouring of many desert sands, usually some shade of red. There is often also efflorescence of soluble salts on the surface. During these reactions crystallisation of salts may occur, and this may cause splitting of solid rocks, just as in the freezing of water.

A very common phenomenon in desert regions is a brown or black shiny crust on the rocks, the so-called 'vernis du désert,' which consists of oxides of iron and manganese. It is probably due to evaporation of water brought up by capillarity, and containing salts of iron and manganese and chlorides in solution. It is thoroughly characteristic of deserts, both ancient and modern, and according to Walther it affords a sure test of the prevalence of such conditions.

It appears that true desert sands often originate by the simple breaking up of crystalline rocks into their constituent crystals, without perceptible alteration of the minerals themselves, but it is not clear how this is brought about.

Igneous rocks often weather in a characteristic way by a process which is described by Richthofen as *desquamation*. This consists in the separation and dropping off of large scales parallel to the surface, and in this way gigantic screes are often formed. Large rock-masses when at a high temperature are often fractured by radial clefts due to sudden cooling, especially by showers of rain.

The processes here outlined are described by Walther as dry weathering, and they are stated by him to be almost entirely due to the action of strong solutions and high temperatures; consequently they differ very markedly both in kind and in origin from the ordinary weathering which occurs in moist and temperate climates.

Weathering in Temperate Regions.—The type of weathering which prevails in regions of temperate climate is to a certain extent a combination of all the others, but naturally each exists in a less marked degree than in districts where the climatic conditions are more extreme. There are also to be noted considerable seasonal variations. In winter frost action is dominant, whereas in spring, summer and autumn water plays a more conspicuous part. It is only in specially dry seasons and in localities where the climate is unusually arid that wind action and dry weathering are of any importance. It must, however, be borne in mind that climatic conditions, and especially the rainfall, show wide variations within very limited areas. To take one case only, the average rainfall of the western coast of the British Isles is much higher than that of the east coast, so that it is difficult to compare the activity of weathering processes in the two regions. Elevation above sea-level is also an important factor, and even in the comparatively low mountains of the British Isles the higher portions show conspicuously the effects of frost-shattering. Temperate regions are much less subject than others to sudden changes of temperature, so that this agent produces only a small effect. On the whole, perhaps, solution and chemical disintegration are the dominant features of weathering in these regions, while frost action is restricted to a small part of the year.

Weathering under Arctic Conditions.—Owing to the low temperature, chemical action is less vigorous and the organic agencies are almost inoperative. By far the most important weathering agent is the expansion of water on freezing, which shatters the rocks, breaking them up into markedly angular fragments. This is the cause of the strikingly sharp peaks and ridges which are so characteristic of the mountains of high latitudes, and of the highest peaks in other regions above the snow-line. Under these conditions decomposition of minerals is at a minimum, and the dominant process is one of disintegration, which leads to the accumulation of great masses of fresh rock-material. Over the permanently snow-covered areas of the arctic zones weathering must be almost non-existent.

(2) Transport and Corrasion

The material which is loosened by the various processes of weathering described in the last chapter is subjected to further influences which remove it from its former situation and deposit it elsewhere, and these processes of removal are summed up under the general designation of *transport.* To effect transport mechanical energy is required, and this energy is supplied by gravity acting alone, by wind, and by moving water and ice.

Every moving particle is capable of doing a certain amount of work; and the kinetic energy of the transported particles, whether falling freely under the influence of gravity or carried along by wind, water or ice, is able to overcome the cohesion of other particles, so that rock-fragments, when once loosened from their beds, form effective graving tools by which the surface is carved out. It is difficult, therefore, to separate clearly the effects of transport and corrasion, as the latter process goes on concurrently with the former. It will be most convenient to consider the two processes together, since to treat them separately would involve much needless repetition.

Agents of Transport.—The chief agents of transport are: gravity, wind, and especially water both in the liquid form and when solidified into snow and ice. It is hardly necessary to point out that, besides these, other agencies sometimes come into play to a small extent, such as animals, which may carry small quantities of material for long distances, and by their burrowing and scratching sometimes facilitate the effects of wind, gravity or water. The results produced are so small as to be practically negligible.

Gravity.—When material is disintegrated in any of the ways described above under the head of weathering, the action of gravity tends to cause it to seek a lower level. When rock-fragments are broken from the face of a cliff or from a steep slope, either by expansion of freezing water or by changes of temperature, they will fall or roll to the bottom, and will there give rise to those accumulations of fallen material which are such a conspicuous feature of mountain scenery in all climates. These accumulations are known as *screes*, and some very fine examples are to be seen in the English Lake District: the well-known screes on the south-east side of Wastwater may be specially mentioned.

A similar effect on a smaller scale is universally found wherever rocks are being weathered *in situ*: if the slopes are steeper than the natural angle of rest of the loose material, this will slide down and will accumulate at the foot. It appears that for this reason there is a constant slow downward creep of soil and loose material on all slopes, but this effect is in part due to the presence of moisture.[1]

Material falling under the influence of gravity possesses kinetic energy, and is capable of doing work. It can often be observed that when a block larger than usual has fallen down a scree-slope its path is marked by a trail of fresh fractures and well-marked scratches on the weathered surfaces of the older fragments. This shows that every falling block does its share in comminuting the older fragments, that is to say, it helps in the process of corrasion.

Although the direct action of gravity, as such, appears to be comparatively unimportant, it must not be forgotten that in ultimate analysis all the manifold effects of water, snow and ice are due to this force, and not to any peculiar property inherent in the water itself. Perhaps the most important of the phenomena which are directly due to gravity are landslips and avalanches, but even here the influence of water is traceable.

Wind as a Geological Agent.—In our own country and in other temperate climates the geological effects of wind are not very conspicuous, partly because of the thick coating of vegetation which acts as a shield for the loose material, and partly because of the prevailing dampness, which prevents the formation of dust to any great extent. The greater part of the dust, which is sometimes conspicuous even in Britain, is of artificial origin, being derived from roads; and it is only in certain sandy districts, such as the country round Aldershot and in parts of East Anglia, and more especially on the western coasts of the island, that wind action is of any considerable importance. To obtain

[1] Davis, *Physical Geography*, p. 267.

a true conception of the geological importance of wind we must turn to a desert region, where it is by far the most potent agent both of transport and corrasion.

It is to be noted that transport by wind possesses one special peculiarity in that material may be, and often is, carried uphill against the influence of gravity. This peculiarity is to a certain extent shared by ice transport. Fine dust may also be carried by wind over water areas, and this is by no means uncommon. The rain which falls in the south of Europe, for example in Sicily, is often quite turbid owing to solid matter in suspension, derived from the deserts of Africa, and this affords a means by which small organisms and spores and germs of larger organisms may be distributed over wide areas. In volcanic eruptions also enormous quantities of fine dust are carried into the air, and spread far and wide. The dust from the celebrated eruption of Krakatoa in 1883 was carried by air-currents in the upper layers of the atmosphere all over the world, and produced most remarkable sunset effects even in Europe.

CHAPTER III

RIVERS

Running Water as an Agent of Transport and Corrasion.—Under temperate conditions of climate and general surroundings, by far the most important agent of transport and corrasion is running water. It may be said that in temperate latitudes with a normal rainfall the existing relief of the land is due almost entirely to this cause, the effects of gravity and wind being very subsidiary.

Within the last few years the subject of water-denudation has received special attention in America, in certain parts of which the conditions are much more simple than in Europe: the phenomena are particularly well displayed in some of the Western States of the Union, and especially in the so-called Great Basin region. Here a simplicity of geological structure, combined with uniformity of conditions and absence of disturbing factors, have produced a degree of regularity which has enabled the United States surveyors to work out the general laws governing stream-erosion, and to formulate them clearly in a manner which is of general applicability. The earliest attempt in this direction was Gilbert's classical Report on the Geology of the Henry Mountains,[1] which has served as the foundation of all later work of the same kind. Of late years Gilbert's conclusions have been much extended by many writers, and in particular by W. M. Davis and I. C. Russell.[2]

The Energy of a Stream.—The starting-point of Gilbert's theoretical conclusions is the conception that every stream possesses a definite amount of energy, depending on its volume and velocity. The volume of a given stream is regarded as a fixed quantity; but the velocity depends on several other factors, and in particular on the slope or declivity. Friction between the flowing water and the sides and floor of the channel is also taken into consideration, so that the form of the channel is also of great importance. The energy of a stream is partly

[1] Gilbert, 'Report on the Geology of the Henry Mountains' (*United States Geol. Survey*). Washington, 1880.

[2] Davis, *Physical Geography:* Boston, 1898. Russell, *River Development:* Progressive Science Series; London, 1903.

utilised by friction and partly by the transport of solid matter in suspension. As the energy is a fixed amount, there is evidently a close relation between friction and transport, since their sum is a constant.

Material which is simply carried along in suspension has little geological effect, but the coarser particles which are rolled along the bed of the stream perform work by means of the energy imparted to them by their movement. Every moving fragment striking the sides or bottom of a stream has a certain effect in overcoming the coherence of the rock over which the stream flows, and thus removing particles which can be carried away by the running water. This is the most important part of corrasion. The tools employed are rock-particles carried along the bottom of the stream, and the force which drives them is the energy of the stream itself. We thus see how closely connected are the two processes of transport and corrasion.

Load of a Stream.—It is evident that a stream of a given volume and velocity will be able to transport a certain amount of solid material, and this is called the load of the stream. Theoretically, the total weight which can be carried should be unaffected by the state of division of the material, provided the size of the particles did not exceed the maximum which could be transported by the given stream; but it is found that in reality a stream can carry a larger load of fine detritus than of coarse, or, as Gilbert puts it, it is easier to carry ten particles of one grain than one particle of ten grains. Hence the effective load of a fully loaded stream depends on the fineness of division of the particles. Since the energy is a fixed quantity, the product of velocity and load is constant; hence also the velocity of a fully loaded stream is controlled by the state of division of the load. Evidently, therefore, there must be a certain condition when velocity and load are nicely balanced, and the stream is able to perform a maximum of work in transport and corrasion. If the load is too great, the velocity is checked and some of the excess of load must be deposited.

It was pointed out many years ago that increase of velocity increases the transporting power of a stream in much more than the simple ratio, and Hopkins showed that the weight lifted should vary theoretically as the sixth power of the velocity. However, it is found by experiment that the actual ratio is somewhat less than this. The very rapid increase of transporting power as the velocity rises explains the powerful effect of floods. If a stream during a flood runs three or four times as fast as usual, its transporting power will be multiplied several hundred times, and it will be able to carry with ease boulders which at other times would be quite immovable.

The Curve of Erosion.—In the case of most streams the upper part of the course is the steepest, while near the mouth the slope, and consequently the velocity, becomes less. This decrease of velocity diminishes the power of transport, and some of the load must be thrown down. Hence it follows that a stream deposits material in the lower part of its course while it is still corrading near its head. In the same way minor variations of slope in the course of a stream will lead to alternate regions of deposition and corrasion. Suppose that at some period of its existence the course of a stream, seen in vertical section, shows the form illustrated in Fig. 17 (continuous line), with an alternation of steep and gentle slopes. Where the slopes are steepest corrasion

FIG. 17.—GRADING OF A RIVER-BED.

will take place, and where they are gentle deposition will occur, so that eventually the whole is planed down and levelled up to one uniform slope (dotted line). Such a river-bed is said to be *graded*. If the volume of water and rate of erosion remained uniform throughout, this graded slope would be represented in section by a straight line, but under natural conditions this is not the case. The volume of water increases from the head downwards, while the rate of erosion is less near the sea, since the stream cannot cut down below sea-level, and the limit is soon reached in this part of the course. Erosion is also less

FIG. 18.—CURVE OF WATER EROSION.

(It is a logarithmic curve.)

near the head in consequence of the smaller volume of water. The ultimate result, therefore, of stream erosion is to produce a curve with the concave side upwards, which is commonly known as the curve of water erosion (Fig. 18). This is the form towards which the beds of all existing streams are tending : many of the sluggish rivers of the eastern and midland counties of England have attained it in an excessively flattened form, having a regular slope from source to mouth, unbroken by any sudden changes of slope. On the other hand, most of the rivers of the north and west show numerous rapids, waterfalls and other inequalities in their courses, which prove that they have not yet reached their lowest level of erosion, but are still engaged in planing off projections and filling up hollows, in the endeavour to attain to the uniform curve above described. When a river has reached a stage at which it can no longer appreciably deepen its course it is said to have reached its *base-level;* this term is of American origin, and is rather a misnomer, since the line attained is not horizontal or a level in the ordinary sense of the word, but a curve lying in a vertical plane. *Base-line of erosion* would be a much better term.

It is much to be wished that some suitable word existed in English to express the course of a stream considered in a vertical plane. For this purpose the German term *Thalweg* is generally employed. It appears that in streams which have reached base-line the thalweg is a uniform logarithmic curve with the concavity upwards, while in younger streams, and those still actively corrading, the thalweg is an irregularly curved line.

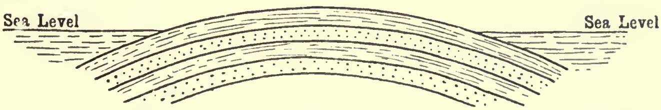


FIG. 19.—CONTINENTAL UPLIFT IN THE FORM OF AN ANTICLINE

The Law of Structures.—Rate of erosion is influenced by the character of the rocks, and especially by their hardness. Since the soft rocks are worn away more rapidly, the hard ones are left as elevations, and this differentiation will continue to become more marked until the soft rocks have reached their base-line of erosion. But the hard rocks are then still undergoing erosion, and this will continue till these also are worn down to base-line. When this is accomplished the differences in elevation will have disappeared, so that the law of structures is only strictly true in the youth and middle age of a region of denudation, and not for the later stages, or maturity. However, with this limitation it may be said that the topographical forms of the earth's surface are primarily due to differences in the hardness of the rocks of which it is composed.

Development of a Typical River-system.—The starting-point of modern theories of the development of drainage-systems is a plain of marine sedimentation, which is uplifted in the form of a simple arch or anticline on a continental scale (Fig. 19). In this simple case the dip of the beds composing the arch will be away from the axis of elevation on either side towards the sea, while the strike is parallel to the axis. Rain falls on the new land surface and tends to run down the slopes along the dip. The rain which falls on the top of the arch sinks into the ground to a certain extent, and issues again as springs a little lower down the slope.

Consequent Streams.—It is assumed that the springs would rise from the ground at approximately equal distances apart, at the corners of a series of equilateral triangles, so that the arrangement of the springs on each side of the watershed or divide would be as shown in Fig. 20. The result of this arrangement is the development of two series of streams, arranged alternately on either side of the divide, and flowing straight down the slopes of the uplifted continent to the

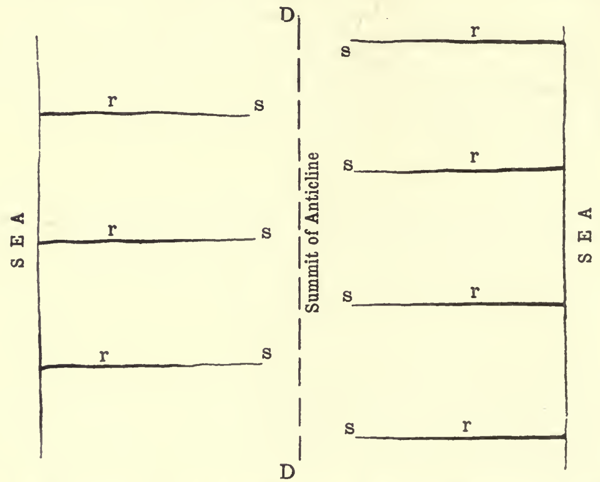


FIG. 20.—INITIAL STAGE IN THE DEVELOPMENT OF A RIVER-SYSTEM.

s, s, Springs; *r, r*, Rivers; *D, D*, Axis of uplift, forming the main divide or watershed.

sea. These are called *consequent* streams, because their formation is a direct consequence of the uplift.

In a short time the effects of denudation make themselves manifest, and their first result is the formation of a half-funnel-shaped hollow round the head of each stream, leading down to a straight valley below (Fig. 21). After a time these hollows encroach on each other, so that from the head of each two passes or cols lead over into the upper parts of the adjoining valleys on either side, while the ground between them stands up as a mountain peak.

Thus we have a watershed or divide of zigzag form separating two series of alternate valleys, each of which has a mountain peak at its head, and from the opposite side of this peak there runs a long ridge, forming the secondary divide between two adjacent valleys (see Fig. 22).

This simplicity of structure is not often maintained, but there is an approximation to it in the case of the chain of Monte Rosa[1] and elsewhere. In spite of many local modifications the zigzag form of the main divides of a district is often recognisable.

The form assumed by the thalweg of a stream under normal conditions, the curve of water erosion, has already been discussed, and it is evident that a section through the ideal continent at right angles to the axis of uplift will show a double curve of this type shown in Fig. 23. The dotted line in the figure indicates the original outline of the

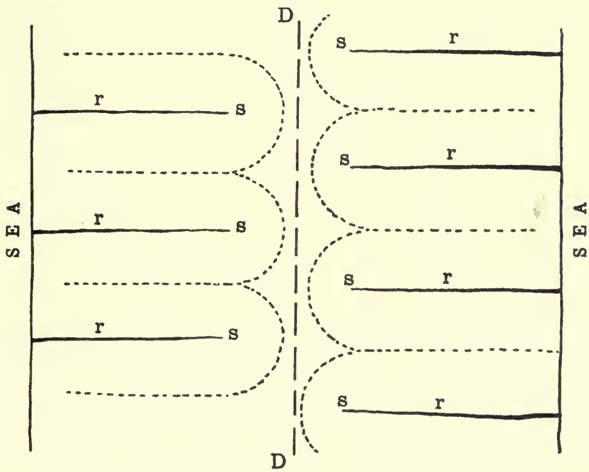


FIG. 21.—FURTHER DEVELOPMENT OF THE SYSTEM.

s, *s*, Springs; *r*, *r*, Rivers; *D*, *D*, Main divide. The dotted lines define the area drained by each river.

continent, which is supposed to have been produced by a symmetrical uplift. We should therefore expect such a region to possess a comparatively level surface near the sea, with slopes gradually increasing in steepness upwards, and culminating upwards in a central mountain-range. This is precisely the structure which is found in the majority of land masses, and it is clearly displayed in the north of England. There are in Northumberland, Durham and Yorkshire a number of large rivers running more or less parallel to one another in an easterly direction to the North Sea: all of these take their rise from a central watershed, the crest of the Pennine chain. These afford the best example in

[1] Marr, *Scientific Study of Scenery*, 1900, p. 77, Fig. 15.

Britain of primary consequent streams of this type. On the western side the symmetry is spoilt by the later dome-shaped uplift of the Lake District and the greater steepness of the Pennine chain itself on this side. Hence the rivers of the western slope are much less regularly arranged than those of the eastern side.

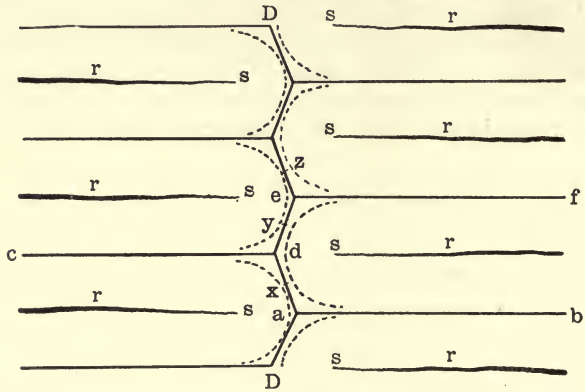


FIG. 22.—*D, D,* Main watershed, with zigzag outline; *ab, cd, ef,* Secondary watersheds; *a, d, e,* Culminating peaks; *x, y, z,* Cols, or passes.

Subsequent Streams.—So far it has been assumed that the streams are simple and constant in volume, without regard to the additions which they receive in the lower parts of their courses, but in reality this is not so. Rain is constantly falling on the land, and must be carried off by surface drainage. Since the conditions are never uniform

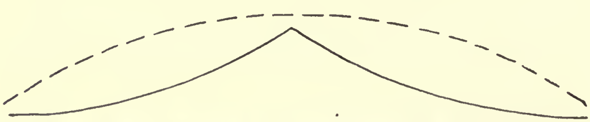


FIG. 23.—SECTION ACROSS CONTINENTAL ARCH,

Showing curve of water erosion on either side of the axis. Dotted line = original surface of arch. Full line = double curve.

the effect of denudation will be to produce an uneven surface; the rain-water will collect in the hollows and will form subsidiary streams, with secondary watersheds between them. The subsidiary streams flow into the main streams as *tributaries*, and the position and distribution of these secondary streams are determined by the geological structure of the land, since they depend primarily on differences of hardness of the underlying rocks.

Let us consider briefly the simplest case, that of a series of originally horizontal strata, uplifted into a continental arch and denuded as before described; and let us suppose that these strata are composed of alternate hard and soft beds. Here the effect of denudation will be to expose alternate bands of hard and soft rock, forming a series of ridges and hollows parallel to the axis of the country and at right angles to the consequent streams. The tributaries will flow along the hollows thus formed, and they are known as *subsequent* streams, because they are formed after the consequent streams (Fig. 24).

If we regard further the relations of these two sets of streams to the underlying beds we shall see that the first set flow down the steepest slope, or dip-slope, of the underlying beds, while the second set flow at

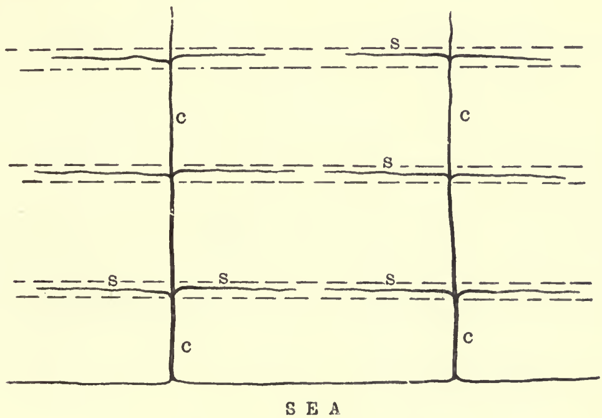


FIG. 24.—PRIMITIVE RIVER-SYSTEM,

Consisting of consequents, or dip-streams, *c*, *c*; with tributaries, subsequent or strike-streams, *s*, *s*, flowing in soft strata.

right angles to this, or parallel to the strike of the beds. Hence consequent and subsequent streams may be spoken of as dip-streams and strike-streams respectively.

River-capture.—Fig. 24 shows the type of river-system which might be developed in a region where perfectly uniform conditions prevailed, but actually such uniformity does not exist. As a result of the diversity of structure and conditions which always occurs in nature, many complications are introduced. In particular the rate of erosion varies in different streams, owing to variations in declivity, volume of water, and other factors, so that some will work backwards more quickly at the head, while others will carve out a deeper valley. In these and other ways the symmetry of the system is destroyed, and in some cases the waters of one river may be diverted into another.

Let us suppose that in Fig. 25 the subsequent stream *b*, a tributary of B, is so much more active than the corresponding stream *a* that it

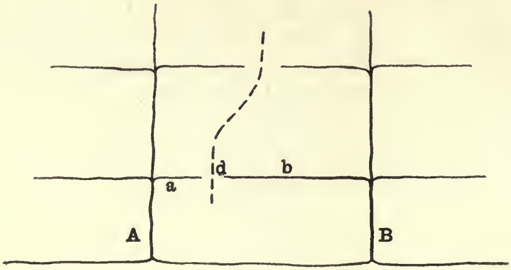


FIG. 25.—INITIAL STAGE IN RIVER-CAPTURE.

The secondary divide, *d*, receding before tributary *b* towards *a*.

has driven back the watershed between the two to *d*, and has been thus enabled to capture the drainage-water which originally flowed into the head of *a*. The extra volume of water thus acquired will still further increase the activity of *b*, so that in course of time it may be able to cut completely through the secondary divide *d*. If the level of *b* is

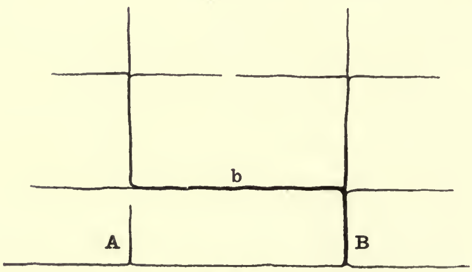


FIG. 26.—RIVER-CAPTURE OR BEHEADING.

The upper waters of A have been diverted by tributary *b* of river B.

here lower than that of A at the point of junction of A and *a*, the water of stream A must be switched off down the valley of *b*, and the lower part of A will be deprived of its water (Fig. 26). This process is known as river-capture, and stream A is said to be beheaded by *b*, a tributary of B.

In this case the lower part of valley A is left dry, or with an insignificant stream only, which appears to be too small to have eroded the valley in which it flows. Such a stream is called a *misfit.*

At the head of the lower abandoned part of valley A is a broad pass or col, leading into valley *b* opposite the great bend of the river. Such a notch at the head of a valley is called a *wind-gap*, and it often gives a clue to the history of the valley.

It is evident that by a long continuance of processes of this kind very complicated drainage systems may be produced, since one particularly active stream may successively capture a large number of others. Such appears to have been the history of the development of the

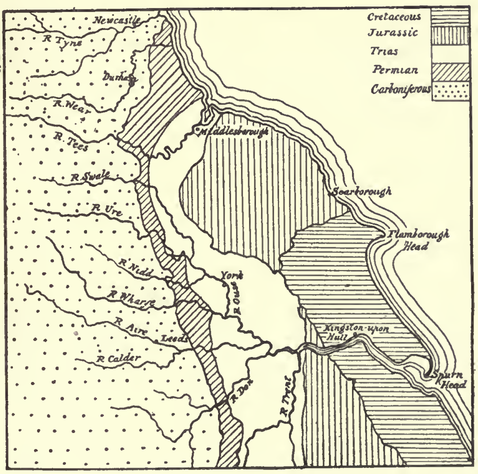


FIG. 27.—MAP OF THE OUSE RIVER-SYSTEM.

present main-drainage system of Yorkshire (see Fig. 27). Leaving out of account certain complications in the eastern part of the county, due to glaciation, the origin of the rivers of this region appears to have been somewhat as follows :

It may be assumed that the system was initiated as a series of dip-streams, consequent upon the uplift of the Pennine chain. This uplift gave rise to a series of rivers flowing eastwards down the dip of the strata to mouths far beyond the present coastline of England. These rivers were the forerunners of the present ones, Tyne, Wear, Tees, Swale, Yore, Nidd, Wharfe, Aire, Calder and Don. The more northerly of these, Tyne, Wear and Tees, have undergone comparatively little change, and are still on the whole consequent streams. With the rest of the rivers enumerated the case is very different. They no longer form independent consequents, flowing separately to the sea, but all unite to form one great river, the Ouse, which joins the Trent, and the two together form the wide estuary of the Humber. The course of the Ouse is approximately north and south, and it flows in the broad belt of soft strata formed by the outcrop of the Trias. This fact is significant, and probably affords the explanation of the whole phenomenon. The

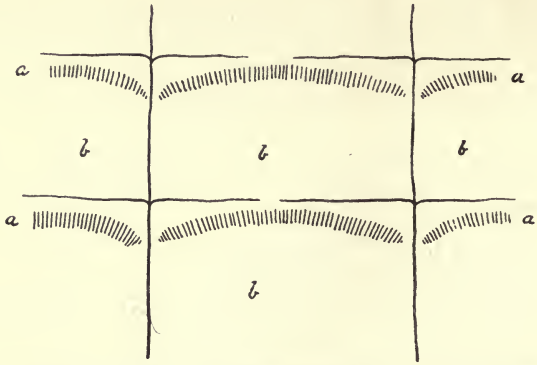


FIG. 28*a*.—PLAN. *a, a*, Escarpments; *b, b*, Dip-slopes.

present course of the Aire may be regarded as a direct continuation of the Humber, and this forms one consequent stream. This consequent developed subsequents, and one of these, working back along the soft Triassic strata, was able to capture the next consequent, and so on successively for the rest. The Ouse, however, has not yet succeeded in capturing the head waters of the Tees, although the watershed between them has been reduced, by the working back of the tributaries of the Ouse, to only 150 ft. in height.

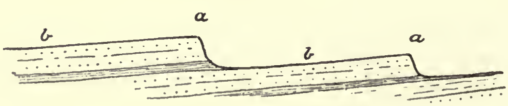


FIG. 28*b*.—SECTION ACROSS ESCARPMENTS, ALONG THE DIP.

a, a, Escarpments; *b, b*, Dip-slopes.

Dip-slope and Escarpment.—The Law of Structures states that hard masses tend to stand up as eminences, while soft ones form hollows, and this law makes itself manifest in the relief of an area undergoing denudation by river erosion. Assuming simple ideal conditions, as before, the tract in question will be traversed by a series of subsequent valleys, parallel to the coast and at right angles to the consequent streams. Since the general dip of the area is towards the sea, each of these valleys will be limited on the seaward side by a steep slope or *escarpment*, and on the landward side by a gentle dip-slope. This can be well seen in the case of some of the larger valleys of the eastern Midlands. The valley of the Cam and Great Ouse is bounded on the south-east by the escarpment of the Chalk, which is comparatively steep, and on the north-west by the very gentle slopes of the Lower Cretaceous and Upper Jurassic beds, which here dip to the south-east at a very low angle. Owing to the contour of the ground these escarpments do not form straight lines, but assume a curved form, as shown in Fig. 28*a*. When denudation has proceeded so far that these scarp-slopes attain a considerable size, they may themselves give rise to

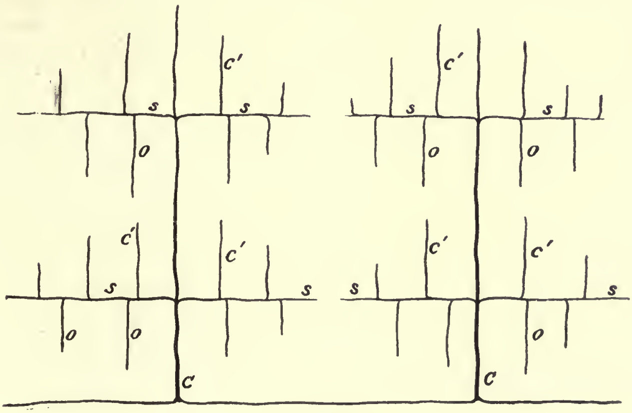


FIG. 29.

C, C, Consequent streams; *s, s*, Subsequent streams; *o, o*, Obsequent streams; *c′, c′*, Secondary consequent streams.

small streams, tributaries of the subsequents: these will flow in a direction opposite to that of the consequents, that is, away from the sea. They may also be described as flowing against the dip of the beds. Streams of this kind are distinguished by Davis as *obsequent* streams (*o, o, o*, in Fig. 29). In a similar way small secondary consequents will develop on the dip-slopes (*c′, c′, c′*), so that the whole system eventually becomes very complicated.[1]

Meanders.—When a stream has reached its base-line of erosion it can no longer cut downwards; but it still possesses energy, which must be used up somehow, and this energy is employed in lateral corrasion. So long as a stream is quite straight the corrasive effect

[1] S. S. Buckman, *Natural Science*, 1899, p. 273.

on both banks is equal, but so soon as any deviation from straightness occurs the current impinges with greater force on the concave side of the curve, so that the banks on that side are eroded, while there is a tendency for deposition to occur in the slack water on the convex side, so that the course of the stream is gradually shifted and the curves become more and more marked. In sluggish streams flowing through level tracts this formation of curves goes on to a great extent, and gives rise to what are known as *meanders* (Fig. 30). Many of our English rivers exhibit the phenomena of meandering in a very high degree.[1] This process obviously occurs at a late stage in the life-history of a river, and very pronounced meandering may be taken as an indication of old age.

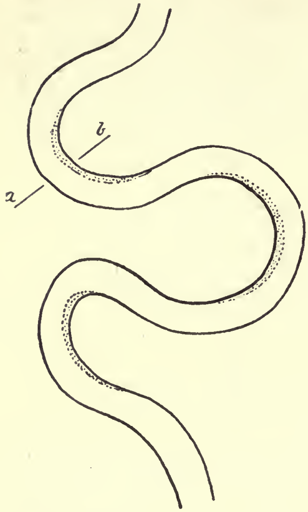


Fig. 30*a*.—River Meanders, showing deposition at the convexities.

In many cases the amplitude of these curves becomes very great and the windings very complex, so that the distance separating two points of the course may be very small in a straight line, although a long length of river channel may intervene between them. In some cases the river may eventually break through the narrow neck of land which separates the two reaches, abandoning the intermediate part of its channel. Such diversions are specially prone to occur during floods, and are much assisted by the steeper grade which must exist between two such points, as compared with the old channel. Such abandoned channels are common along the lower reaches of many large rivers, and along the

Fig. 30*b*.—Section across *ab* in 30*a*.

lower course of the Mississippi they have given rise to a series of crescent-shaped lakes, which are there known as *ox-bows*. Similar structures on a small scale may be seen along many a winding English stream.

Meanders not only tend to increase in amplitude and complexity,

[1] *Loc. cit.* p. 286.

but the whole curve moves bodily down-stream, since the current always sets more strongly against the down-stream bank. Thus in course of time a river may work over a very considerable area of ground, and will give rise to a large level plain, or alluvial flat, which is bounded on either side by fairly steep slopes. A plain formed in this way is called a meander-belt, and within this area the whole of the soil must consist of material which has been sorted and redeposited by river action, down to the base-line of erosion.

One of the conspicuous results of this process is the formation of a river valley having a peculiar cross-section, with a flat floor and comparatively steep sides, at any rate in certain parts. All valleys soon depart from ideal straightness and become winding, so that each side is bordered by a succession of rocky spurs, with tributary valleys running up between them. When looking up such a valley we see a succession of rocky points, one behind the other, running out from either side alternately, and so long as downward corrasion continues these only become more and more accentuated. But when lateral corrasion comes into play the meanders cut into these spurs and remove their ends, producing a wide flood-plain or meander-belt of the type above described, bordered on either side by the truncated ends of the spurs.

So long as the conditions remain unaltered a river may continue to increase the width of its meander-belt; and it is possible that the width of this may eventually become so great as to encroach upon the meander-belt of another river, so that their curves intersect. In this case the river which happens to be at the lower level will have the advantage, and will tap the waters of the other. The latter will then forsake the lower part of its own channel, and will be permanently diverted into the other stream. This is one method by which beheading and capture may occur.

Rejuvenation of Rivers.—Let us next consider the case of a river which has already reached its base-line and has established a system of meanders. Then, at a comparatively late stage in its history the region is uplifted, so that the river is again enabled to effect downward corrasion. Such a renewal of the activity of a river may be called rejuvenation. Lateral corrasion will then cease or will become comparatively unimportant, and the energy of the stream will be concentrated upon cutting downwards, so that its channel will be sunk below the general surface of the land. But the plan of its course will be preserved, so that the river will flow in a series of meandering curves in a deep valley cut out of a comparatively level high-lying plateau. *Incised meanders* of this kind are an indication of uplift subsequently to the establishment of the base-line of a river. One of the most striking examples is afforded by the deep winding gorge of the Moselle, while in our own country the Wear between Durham and Sunderland flows in a similar valley. The great bend of the river through the city of Durham is a conspicuous feature; it encloses the cathedral and castle on three sides, and to it was due the strategic importance of the city in olden times. Appleby occupies a very similar situation in a great loop of the Eden, and this was also a strong place in very early days.

The Law of Unequal Slopes.—If the uplift which has produced the primary divide of a river was asymmetric, so that the slope on one side is steeper than that on the other, denudation will be more rapid on the steeper side, so that the watershed will gradually work back towards the

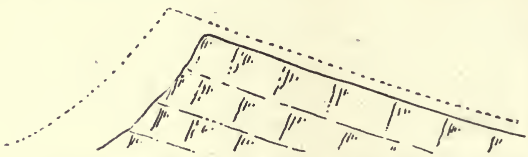


FIG. 31.—RECESSION OF WATERSHED, DUE TO UNEQUAL SLOPES.

more gentle slope, as is shown in the section in Fig. 31. Here the dotted line represents the original form of the divide, and the unbroken line its form at a later stage. In this case the watershed is receding towards the right: the recession will obviously be most rapid at the heads of the principal streams, so that by this means alone an originally straight divide may assume a zigzag form.

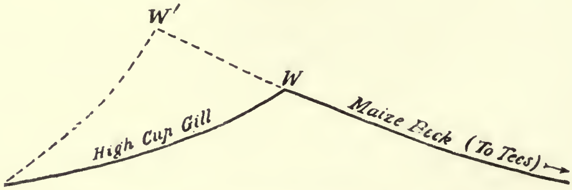


FIG. 32.—DIAGRAMMATIC SECTION THROUGH THE HIGH CUP VALLEY.

W, Present watershed; *W′*, Ancient watershed. The continuous line shows the present surface, the dotted line the ancient one. (After Marr.)

This process is very well illustrated by the streams which drain the northern part of the Pennine range, along the Cross Fell escarpment. This escarpment is determined on the west by the great Pennine faults, which have produced a steep slope facing the Eden valley, while the east side consists of a gentle dip-slope of Carboniferous rocks. Consequently the head-waters of the Tees rise close to the edge of the escarpment, and flow eastwards with a very slight fall. On the other hand, the

F. J. Garwood, photo.

(I) HIGH CUP NICK, AND THE WHIN SILL.

J. Romanes, photo.

(II) SIDUAL ELEVATION IN A PLAIN OF RIVER EROSION. EILDON HILLS, MELROSE.

scarp-streams flowing west have a rapid fall, and have excavated deep valleys. The most striking example is High Cup Gill, near Appleby,[1] which heads far to the east of the highest point of the range, and has cut back into the valley of a tributary of the Tees (Fig. 32).

High Cup Gill runs through a deep gorge into the wide Eden valley. On ascending it and reaching High Cup Nick, at the head of the valley, a broad valley is found, sloping gently down to Maize Beck, a tributary of the Tees. In this valley a stream runs over the dip-surface of the Tyne Bottom limestone. This valley once extended much farther west, but it has been cut into by the High Cup stream (Plate VIII (i)), and remains of the floor of the old valley can still be seen as a kind of ledge, sloping eastwards, on either side of the head

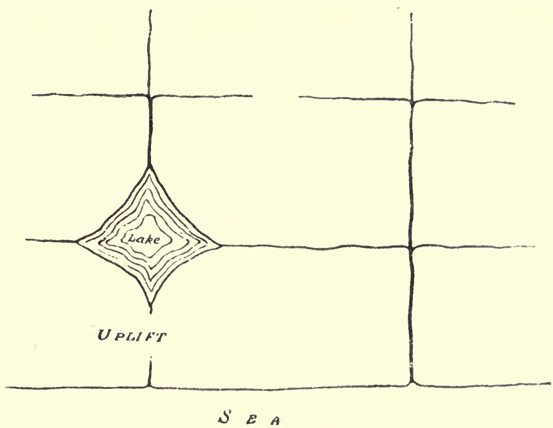


FIG. 33.—DIVERSION OF A RIVER BY PONDING.

of High Cup Gill. In time the head of this latter valley will recede to Maize Beck and this important stream will be diverted into the Eden drainage, and the Tees will be deprived of one of its most important head-waters.

Diversion of Streams by Ponding.—Besides the methods of diversion above described, which depend upon variations in the rate of erosion in different cases, streams may also be diverted and beheaded by a method known as *ponding*. If an uplift of local character occurs in the lowe part of the course of a river, forming a barrier, the water will accumulate behind it, giving rise to a lake (Fig. 33). The dam may eventually become so high that the lake overflows over the col at the head of one of its tributary valleys, and thus its drainage is diverted into another system. The beheaded remnant of the original consequent

[1] Marr, *Geogr. Jour.* vol. vii., 1896, p. 608.

may still be seen in the old valley, below the barrier. In course of time the lake will become silted up and converted into an alluvial plain, over which the river meanders.

It is evident that ponding may be produced in a variety of ways, since the barrier may be formed otherwise than by uplift: for example by a landslip, or even by an avalanche. However, such dams are usually of a temporary nature, and give way suddenly when the pressure of water behind them becomes too great. Somewhat similar dams formed of moraine material are often of a very permanent nature, as will be shown when we come to consider the formation of lakes.

Consequent and Inconsequent Drainage.—In the cases hitherto considered the arrangement and distribution of the river system are directly dependent on the geological structure of the rocks on which it rests, and are a consequence of the uplift of the area. Such a drainage system may be called *consequent*. But there are also cases in which the drainage system does not appear to have any direct relation to the structure of the underlying rocks, but is quite independent of it. Such drainage systems are spoken of as *inconsequent*, and they may be produced in various ways, of which the two following are the most important:—

A. *Antecedent Drainage.*—After the establishment of a complete river system in any given area, and its adjustment to existing conditions, part of the area may undergo uplift, so that a barrier is produced across the course of a stream. If the uplift is relatively sudden, ponding will occur, as before explained. But the uplift may be so slow that stream erosion can keep pace with it, so that the river is able to saw through the obstruction as it rises, and thus keeps its channel open. The best examples of this process are found in the rivers of Northern India. The Indus and the Brahmaputra both rise on the northern side of the main chain of the Himalayas, through which they cut in great gorges and flow to the Indian Ocean. In this case it is evident that the rivers were in existence before the mountains, which date from a comparatively late period in the geological history of Asia, viz. from the Miocene. It is impossible to account for their present relations on any other supposition. The rise of the mountain-chain was so slow that the rivers were able to keep open their former channels during an uplift of very many thousands of feet. Since the origin of the rivers was antecedent to that of the principal tectonic features of the district, a drainage system of this type is said to be *antecedent*.

B. *Superimposed Drainage.*—The second case is where the arrangement of a river system has been determined by the structure of a set of rocks on which it was originally formed, but which have been since removed by denudation, so that the rivers now rest on the underlying rocks of different structure. They have completely cut through the rocks which originally determined their distribution, and have settled down on the subjacent strata. Such a drainage system is said to be *superimposed.*

The Drainage of the English Lake District.—A good illustration of superimposed drainage is afforded by the English Lake District (Fig. 34).

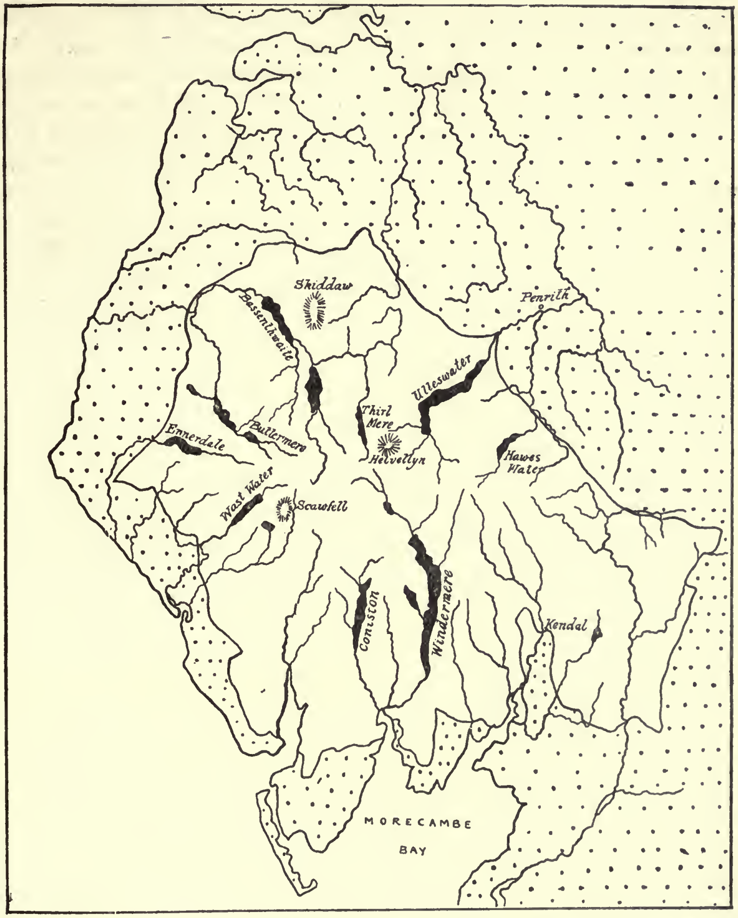


FIG. 34.—MAP OF THE LAKE DISTRICT, SHOWING RADIAL DRAINAGE.

The dotted area represents Carboniferous and Newer Rocks; the plain area, Silurian and Ordovician.

The central part of this area consists of a mass of highly folded and faulted Lower Palæozoic rocks, which have a general strike approximately in a N.E.-S.W. direction. This is surrounded by a more or less continuous ring of Carboniferous and newer rocks, which, neglecting minor variations, dip away from the centre in all directions. The whole district may thus be regarded as a denuded dome, from the centre of which the newer rocks have been removed, so as to expose the Palæozoic core which was folded and faulted before the occurrence of the uplift which produced the dome. The arrangement of the drainage system confirms this view. The dome is not strictly circular, but slightly elongated in an east and west direction, and the rivers take their rise from a short watershed, which runs from the Scafell group in an easterly direction. The arrangement of the principal valleys, in most of which are considerable lakes, is distinctly radial. The upper parts of these valleys lie in Lower Palæozoic rocks, and there is no relationship observable between the dip and strike of these rocks and the general lie of the valleys, regarded as a whole and apart from local details. But when the streams pass on to the Carboniferous and New Red rocks they become dip-streams or consequents of the ordinary type. It may be concluded, therefore, that this drainage system was initiated on the original surface of the dome-shaped uplift, which Dr. Marr believes to have been of Tertiary age, though direct evidence on this point is wanting. In course of time the cover of newer rocks was removed by denudation from the centre of the district, and the streams settled down into, or were imposed upon, the older rocks. Since this time their courses have undergone slight modifications, owing to peculiarities of structure in the older rocks and the existence of planes of weakness in them, as pointed out by Dr. Marr in his Presidential Address to the Geological Society in 1906.[1] But there is no doubt that the general direction of the main valleys is substantially the same as when the streams were first formed, as a consequence of the uplift, and so far as regards the older rocks this is a clear case of superimposed drainage.

The Influence of Ice on River Erosion.—Many of the large rivers of the northern hemisphere become frozen to a considerable thickness in winter, and it is necessary to take into account the possible influence of this state of things on their geological activity. In Britain the geological effect of river-ice is probably not great, although Lyell long ago pointed out that in the Tay and other rivers pebbles are often carried along by floating ice; and sometimes after a hard winter important changes are brought about on the banks and in the beds of British rivers by a sudden break-up of the ice, especially if, as is commonly the case, the thaw is accompanied by a flood. But to realise the full effects of river-ice we must turn to the colder regions of the globe, such as Siberia, Canada or Alaska. Here the freezing-up of the rivers in winter and their release in spring is a regular annual occurrence, and its powerful effect has long been noticed.

[1] *Q.J.G.S.*, vol. lxii., 1906, p. cii.

Rocks and boulders partially submerged are often surrounded by large masses of ice, which form round them as a centre. If this mass of ice becomes large in proportion to the mass of the boulder, the buoyancy of the ice may enable it to float off and carry the boulder with it. A process analogous to this occurs in connexion with what is known as *ground-ice*. In many rapidly flowing rivers in cold countries ice forms along the sides and bottom of the channel long before the surface is frozen over. Under the influence of the current masses of this ground-ice or anchor-ice rise to the surface and bring up with them stones of various sizes, which they may transport for long distances. This process seems to be of great importance in many of the rivers of the arctic and sub-arctic zones.

In the case of a river of considerable length flowing from south to north in high latitudes, on the approach of spring the ice will break up first on the upper southern part of the course, so that floods of water and half-melted snow, bearing much detritus, will be carried down on to the unmelted ice surface farther north. In this way ice-barriers are frequently formed during spring floods, so that the waters are held back and often diverted into new channels. The bursting of such ice-barriers may cause sudden floods, which may produce very well-marked effects, both in the way of transport and corrosion. This phenomenon is well known in the case of several European rivers, notably the Vistula, and causes extensive floods nearly every year in the neighbourhood of Danzig. This helps to account for the changes that have taken place in historic times in the lower course of that river.

CHAPTER IV

EARTH SCULPTURE

Topographic Forms of River Valleys.—It is a self-evident fact that the characters of rivers vary within very wide limits. There is a striking difference between the impetuous torrents of mountain districts, with a swift current of clear water, abounding in rapids and falls, flowing over a rocky bed, and the slow and tortuous streams of the plains, with their sluggish currents of muddy water, bounded by marshy banks of clay and silt. These differences are due to various causes, of which the principal are the character of the material over which the river flows and the extent to which denudation and deposition have gone on in the district in question. In other words, the topography of any river valley depends on several factors, of which the chief are the hardness of the rocks, the relative age of the river, and the climate. Mountain torrents are young rivers, and the accidents which diversify their courses are due to incomplete denudation, while the rivers of the plains are in an advanced state of development. They have long since established their base-line, and have become completely adjusted to the structure of the country. It must not be forgotten that in such rivers erosion is practically at a standstill. The general level of the surrounding country is not being lowered, and the only corrasion which is taking place is in a lateral direction. Since the tendency of erosion is to reduce the bed of a river to one uniform curve, the very existence of inequalities, such as falls and rapids, is in itself evidence that the process is incomplete.

Pot-holes.—We have seen that the actual scooping out of a river-bed is performed chiefly by the action of solid material, such as stones and sand, carried along by the current, aided to a certain extent by solution. It is necessary now to inquire somewhat more closely how these tools do their work. The flow of a stream is never a perfectly uniform process, but the velocity varies in different parts, so that differential movements are set up. Inequalities in the bed produce minor currents and eddies which often possess a circular or swirling motion, and these cause a grinding movement of the pebbles on the bottom. Thus hollows of a more or less circular form are produced, and in course of time these may

R. H. Rastall, photo.

(I) POT HOLES. HARTA CORRIE, SKYE.

R. H, Rastall, photo.

(II) EARTH SCULPTURE IN HOMOGENEOUS DEPOSIT, NATAL.

become very pronounced, forming deep holes with curved sides in the solid rock (Plate IX (i)). Such hollows are commonly known as pot-holes, and they are conspicuous features of most streams that flow over a rocky floor. Pot-holes often coalesce, and thus carve away large masses of rock. The formation of pot-holes is a very important method of erosion, and its effects are often specially marked in the case of streams that carry little sediment, as, for example, when a river flows through a lake and is thus deprived of the solid matter in suspension by settlement. This process can be well seen in the case of the stream which flows from Watendlath Tarn in the Lake District, and which runs for some distance over a rocky barrier. The bed of the stream is carved into a succession of large pot-holes. Other excellent examples occur in the Glens of Antrim in the streams which flow in gorges cut in the edge of the great basalt plateau.

Earth-pillars.—One of the most striking cases of the dependence of topographic form on rock structure is afforded by the so-called earth-pillars, which are found in certain parts of Scotland and the Tyrol. When the rock which is undergoing denudation by rain is not homogeneous, but consists of large blocks of hard material embedded in a matrix of finer texture, the erosive effect of the rain is very unequally distributed. The large blocks act as shields to the finer material below them, which is thus protected from removal, while the material not thus protected is carried away. If the blocks are but sparingly distributed as in boulder clay and in some conglomerates, the result is that the large blocks are left standing on the tops of columns of varying height.[1]

Influence of Joints.—When a rapid stream flows over a surface composed of a well-jointed rock which is not soluble, it can often be seen that the surface does not possess a smooth, uniform curve, but is rather composed of a series of steps parallel to the joint-planes of the rock. In this case it is evident that the rock is not worn away by the grinding of fine particles, but by the breaking off of blocks along the joint-planes. Somewhat related to this is the action of streams on limestone rocks, where the effects of ready solubility are superadded to those of the ordinary processes of mechanical erosion. Solution takes place most readily along joint-planes, which are rapidly enlarged, so that streams in limestone districts tend to run in gorges cut along the major joints. Here also the drainage is often underground, in caves and fissures, which are formed in a similar manner.

Waterfalls.—When a stream flows over the edges of a succession of beds of different degrees of hardness it often forms waterfalls, which are

[1] See *Brit. Ass. Geol. Photographs*, Third Issue, Nos. 755 and 756, with description by Sir A. Geikie.

marked features of many incompletely graded streams. The most favourable conditions for the formation of a waterfall exist when a hard and well-jointed layer overlies one of a softer nature. Such is the origin of the much-described Falls of Niagara, where hard and well-jointed beds of limestone, the equivalent of the well-known Wenlock Limestone of England, overlie a softer shale, representing our Wenlock Shale.

The origin of many British waterfalls is very similar, and as an example we may take High Force in Upper Teesdale. In this part of its course the Tees flows over Lower Carboniferous rocks, chiefly limestones and shales, with a thick bed of intrusive igneous rock, the Great Whin Sill, of somewhat superior hardness. The actual fall is about 70 ft. high, and the upper part of the precipice is formed by the Whin Sill, while the lower part consists of more or less metamorphosed limestones and shales. The igneous rock is very well jointed in the form of vertical columns, and, so long ago as 1823, Sedgwick[1] remarked that 'the interest of the scene is greatly heightened by the singular contrast presented by the horizontal beds which form the base, and the prismatic masses of trap which form the crown of the escarpment.' A few miles farther up the valley of the Tees is another well-known fall, Caldron Snout, also determined by the Whin Sill; and in other parts of the north and west of England are many fine falls whose existence depends on hard beds of limestone overlying softer rocks. Of somewhat similar origin are the Falls of Lodore, near the head of Derwentwater. Here the hard volcanic rocks of the Borrowdale series form a steep scarp above the softer Skiddaw Slates, which underlie them and form the floor of the main valley, into which the Lodore stream descends as a tributary.

During the last few years much attention has been attracted by the great Victoria Falls on the Zambesi, which were originally discovered by Livingstone. In this case, as at Niagara, the river suddenly plunges from a high tableland into a deep chasm, which is continued as a gorge or cañon for many miles below the falls themselves. By its discoverer and other early writers this gorge was considered to be a crack formed during an earthquake or some other convulsion of nature, but recent research has shown that it is primarily due to water erosion acting on well-jointed rocks.

This region has recently been investigated by Mr. A. J. C. Molyneux[2] and by Mr. G. W. Lamplugh.[3] The Upper Zambesi flows over part of the high plateau of South Africa, and while at a height of some 3,000 ft. it begins a sudden descent over the mountainous eastern margin of the plateau, which here consists of a thick series of lava flows, the Batoka basalts. These rocks are well-jointed and are traversed by well-marked

[1] *Trans. Cambridge Phil. Soc.*, vol. ii. p. 158.
[2] *Geographical Journal*, vol. xxv., 1905, p. 40.
[3] *Geol. Mag.*, 1905, p. 529; *Q.J.G.S.*, 1907, p. 162.

lines of fracture, and these two sets of divisional planes have together constituted lines of weakness which have materially assisted the erosive action of the river. The chief lines of weakness run east and west, with subsidiary ones at right angles, so that the gorge consists of a series of zigzags having corresponding directions. The chasm at the falls is due to one of these planes of weakness, probably a fault, with a vertical belt of soft veinstuff which is easily eroded. The tributary streams below the falls descend into the main gorge by subsidiary falls and gorges having a structure exactly analogous to those of the main river, while above the falls the beds of the tributaries have been graded down to the level of the Zambesi. For some hundreds of miles below the falls the river runs in a series of deep gorges cut through hard rocks, but the angle of slope of the walls gradually decreases, owing to the longer period during which erosion has been able to act, and this affords additional evidence for recession of the falls themselves.

Cañons and Gorges.—The term cañon is popularly used in America to designate a valley of almost any form, but in this country it is most commonly understood to indicate a narrow valley or gorge of great depth in proportion to its width, and having sides of great steepness. The best-known example is, of course, the celebrated cañon of the Colorado: this is perhaps the most remarkable example of river erosion that the world has to show. The conditions of its formation are somewhat peculiar, since the Colorado is one of the very few known examples of a great river cutting through a desert region. Since the action of surface-water and tributaries is practically excluded, the case becomes a comparatively simple one, as we have only to consider the action of the main stream.

The Grand Cañon of the Colorado is some 300 miles long, and has a maximum depth of about 6,000 ft. When regarded in cross-section it is seen to consist of two parts: a wide upper valley having a total breadth of about thirty miles, with a flat floor and sides of moderate slope, and an inner part, the cañon proper, which is very narrow and has walls in places approaching the perpendicular. It is considered that the upper, wide part was formed during a period of more normal climatic conditions than those now prevailing: it is, in fact, a river valley of very ordinary type, due to water erosion and planation. After a time the climate changed, local rainfall practically ceased, and the river began to cut exclusively downwards. In spite of its vast size, it is quite evident that the Colorado cañon is a young valley, in which the processes of denudation are very incomplete. Cañons on a large scale also occur on the Yellowstone, the Snake River, and many other rivers of the western United States.

Although in Britain we possess no cañons on the stupendous scale of these American examples, yet there are to be found cases of deep and narrow valleys which merit the name of gorges. One of the best known of these is the Cheddar Gorge in the Mendip Hills in Somerset. This gorge, whose maximum depth is about 420 ft., has been cut in beds of well-jointed Carboniferous limestone, which dip south at about 20°. On the southern side the cliffs are nearly vertical, while on the northern side the slope is more gradual and often coincides for a short distance with the dip of the limestone. For the greater part of its length the gorge is now dry, but near its lower end a stream issues from the rock. As regards its manner of formation, it has been suggested that the gorge is due, in the main, to the subterranean action of water, which, by enlarging fissures, gave rise to a cave, whose roof eventually fell in.[1]

Many of the most remarkable gorges in Britain are due to special circumstances, viz. to glacial action. Many of the preglacial valleys of Britain appear to have been filled up by ice or drift material, or both, so that the streams were forced to carve out new channels for themselves; and these new channels often possess characters very different from those of the old valleys (cp. Plate X (i)). We shall return to this subject in a future chapter.

Denudation in Limestone Districts.—In many limestone districts there is developed a peculiar type of topography which merits special description. The weathering of limestones differs, in some important respects, from that of other rocks; and this difference is due to two principal causes, viz. the solubility of calcium carbonate in natural waters, and the highly developed system of joints which is nearly always found in such rocks. As a result of these two causes taken together, the greater part of the water circulation in limestone regions is, under ordinary conditions, underground, and this leads to the formation of fissures and caverns, often on an enormous scale.

When rain-water falls on a well-jointed surface of limestone it soon runs into a joint-fissure. Here the action of solution comes into play, and the joint is rapidly enlarged. A constant stream of water falling down a fissure of this kind will eventually produce a funnel-shaped or cylindrical shaft, often leading down to a great depth. Such structures are well seen in the Carboniferous Limestone district of N.W. England, especially in the area to the north of Settle along the valley of the Ribble. The underground circulation of water in this region has been exhaustively studied by the Yorkshire Geological Society,[2] and some interesting results have been obtained. It is found that, on the whole, the flow of underground water in limestone rocks follows the direction of the major joints; but some deviations from this rule occur. A study

[1] This description is copied almost verbatim from Prof. S. H. Reynolds' note on a photograph in the *Brit. Ass. Geol. Photographs*, No. 1587.

[2] *Proc. Yorks. Geol. Soc.*, vol. xiv., 1900–2, p. 1.

of the development of such a system shows that as soon as a channel sufficiently large to admit of a free flow of water is formed by solution a number of other factors come into play which tend to modify the original direction. If the rocks are inclined, erosion is stronger on the downward side, so that the stream cuts sideways. When there are cross-joints the dip may produce a lateral escape along these, so as to give rise to a zigzag course. Up to a certain point erosion is entirely by solution, but as soon as the external opening becomes large enough to admit sand and gravel, mechanical erosion begins. This rounds off the sharp angles of the zigzags and produces a meandering course. As the size of the channels increases there appears to be a tendency to simplification and straightening, and deserted channels often exist. One of the most remarkable features of this region is the vertical shafts or swallow-holes : the largest of these is Gaping Ghyll, which is 365 ft. deep. At the bottom of the shaft is an enormous chamber, 480 ft. long, 80 ft. broad, and 110 ft. high. The underground circulation of water in this neighbourhood is very complex, and some remarkable features occur. In one case a stream which falls down a swallow-hole reappears as a spring on the other side of the Ribble, 12 ft. above the level of the water in the river.

The underground water circulates through the limestone until it reaches the hard and impervious floor of Lower Palæozoic rocks on which the Carboniferous series rests, and it is then stopped in its downward progress. Consequently, the outcrop of the base of the Carboniferous is marked by a line of springs, which are of material assistance in mapping this highly drift-covered area.

The absence of surface water has a peculiar effect on the topography, since it causes the limestone to behave as if it were a hard rock, and to form conspicuous plateaux, which are often bounded by a steep escarpment. The formation of these dry, rocky plateaux is a characteristic feature of almost all limestone districts. In this country they are specially well developed in the Carboniferous area of West Yorkshire, around the head-waters of the Ribble. The bare surfaces of the limestone are locally known as 'clints.' A good example of such a plateau is afforded by Ingleborough. The middle platform of this mountain consists of the thick limestones of the Lower Carboniferous series surmounted by a mass of Yoredale rocks, chiefly shales and grits, forming the higher slopes, with a capping of Millstone Grit on the summit. The surface of the plateau presents a very peculiar appearance : the limestone is so pure that there is no soil, and the whole consists of a bare and corrugated surface of smooth rock, with innumerable joint-fissures, in which ferns and other shade-loving plants grow luxuriantly.

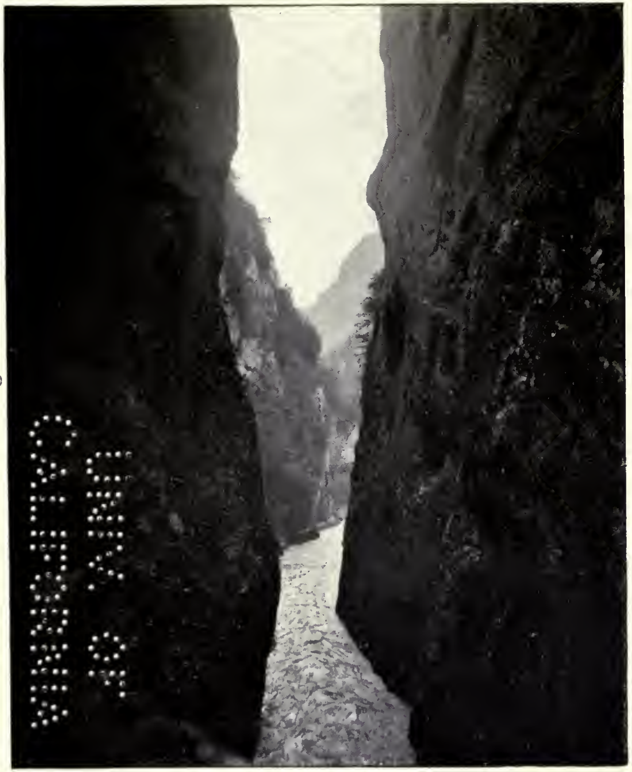
Dry Valleys.—The character of the drainage systems of these limestone districts, both above and under ground, shows that at one time the volume of drainage water must have been much greater than at present. Almost everywhere there are to be found large and deep valleys, now entirely streamless or only occupied by temporary streams during periods of unusually heavy rainfall, but showing everywhere indications of having been eroded by subaerial denudation of the usual type. A good example is the dry valley which extends from a little below Malham Tarn to the top of Malham Cove, at the head of Airedale (Plate X (ii)). Some of the valleys of the Mendips are very similar to this. It may indeed be said that dry valleys occur in almost all districts where calcareous rocks are dominant, and they are common even in the Chalk. The probability is that these valleys were formed during a period of heavy precipitation, either during or just after the Glacial Period; and the idea has been put forward that some of them, at any rate, were formed while the rocks and soil were actually frozen, so that water falling on the surface was not able to penetrate downwards in the usual manner.

In the south-western part of the Austrian Empire, in Carinthia, Carniola and Istria, is a vast spread of dolomite—rock which presents all the features here described in a remarkable degree, and on a much larger scale than in Britain. This region is locally known as the Karst. The great plateaux of Jurassic limestone in the south-east of France, in the neighbourhood of Montpellier, are very similar.

Caverns.—Incidental references have already been made to the common occurrence of caverns in limestone regions; and it may be stated that they are almost restricted to this class of rock, since no other possesses in such a high degree the requisite characters, viz. well-developed joints and high solubility. The formation of caverns is, in fact, very closely connected with the underground circulation of water just described, and caves or caverns, using the term in its popular sense, are only unusually large channels formed by underground circulation and denudation. The best-known caves in Britain are those of the Mendip Hills in Somerset, the Peak district in Derbyshire, and the neighbourhood of Settle and Ingleton in north-west Yorkshire. Caves are sometimes simple, consisting of one chamber only; but more commonly there are several chambers, communicating with one another by means of narrower passages, often of the most complex nature. As would naturally be expected, these narrow passages generally run along the joint-planes of the rock, so that the whole system has a more or less rectangular arrangement. This peculiarity of arrangement shows itself both in the horizontal and vertical planes, so that many caves consist of a series of chambers one behind the other in a step-like manner, with a general downward slope towards the entrance. The connecting passages are frequently vertical or nearly so.

Many caves present features of great palæontological and archæological interest, since they have served as dwelling-places for many

PLATE X



J. J. Lister, photo.

(I) GORGE IN LIMESTONE. AARSCHLUCHT, MEIRINGEN, SWITZERLAND.

G. Bingley, photo.

(II) DRY VALLEY IN CARBONIFEROUS LIMESTONE. MALHAM, YORKSHIRE.

animals and for man, and traces of their occupation are often well preserved in the deposits which have afterwards been formed.

Cave Deposits : Stalactites and Stalagmites.—The water which circulates through limestone rocks is always peculiarly rich in dissolved carbonate of lime, and when this water drips from the roof a certain proportion of it is evaporated, so that the dissolved carbonate is deposited either on the floor or on the roof of the cave. It often forms most beautiful incrustations or long pendent structures like icicles. When these hang from the roof they are called stalactites, and similar cone-like masses on the floors are called stalagmites. When the deposit shows no particular form, it is generally spoken of as calc-sinter or travertine, or sometimes as calcareous tufa. Besides these chemical deposits, caves often contain great accumulations of mechanical sediment carried in by streams, especially during times of flood.

Underground Circulation of Water.—One of the most important applications of geology to practical problems is in connexion with water-supply. This subject is intimately connected with geological structure, and it is one of considerable complexity, so that it is only possible here to give a brief outline of the leading principles.

When rain falls on the surface of the land there are three courses open to it: it may evaporate; or run off at once, ultimately to unite into runnels, streams and rivers; or it may to a greater or less extent penetrate into the rocks. Probably it always penetrates to some extent, so that the exterior portions of the earth's crust always contain a good deal of water. How far this sheet of underground water extends downwards is unknown, and its depth is doubtless very variable in different regions. So far as direct observation extends, in deep mines and borings there is always more or less water present; but there is some indication that the amount reaches a maximum at a comparatively small depth, and falls off again below this. For our present purpose the lower limit of ground-water is of no practical importance, and we have to deal only with the conception of a region at a certain depth saturated with water, and possessing a more or less vaguely defined upper surface, above which the rocks are not saturated. This upper level of saturation, or *water-table*, is of the utmost importance in practical questions of water-supply, since its position is directly dependent upon geological structure, and is the controlling factor in determining the occurrence of springs and in fixing the position of artificial wells.

In regions possessing an abnormally dry climate the relations of underground water are peculiar, as explained later; but in temperate regions it may be said that more water always falls on the surface and percolates downwards than is required to maintain the saturation of the ground-water belt. Consequently, the upper limit of this belt tends to rise, and would do so continuously were it not that the water is usually drained off and kept at a constant level by outflow in the form of springs. Where the geological structure is suitable, the water-level may reach the surface, or even extend above it, forming marshes, swamps or lakes; here the water accumulates until it is enabled to find an outflow in the usual manner, or until a change of climate lowers the level of saturation below the surface. Thus it will be seen that the position of the upper limit of saturation is a function of many variables.

Origin of Springs.—The permeability of rocks to water is very variable, and depends very largely on the composition and texture of the rock. Water naturally penetrates much less easily into a close-grained, compact substance like clay than into a porous rock like sandstone, or into a well-jointed limestone. Thus for practical purposes rocks can be divided into two classes—permeable and impermeable. It must be remembered, however, that these terms are only relative, and have no

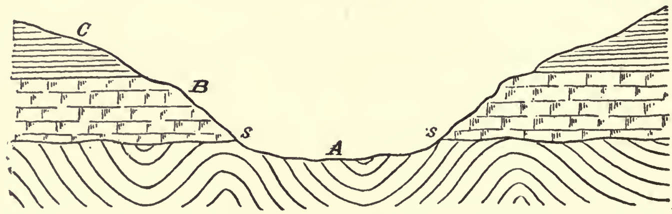


FIG. 35.—DIAGRAMMATIC SECTION TO SHOW THE RELATIONS OF THE OLDER AND NEWER ROCKS IN WEST YORKSHIRE, WITH SPRINGS ISSUING ALONG THE UNCONFORMITY.

A, Highly folded, impervious Lower Palæozoic rocks; *B*, Carboniferous Limestone; *C*, Yoredale Shales, &c.; *s*, *s*, Springs.

fixed values. According to Daubrée,[1] the following are examples of impermeable rocks: clay marl, slate, granite and other massive crystalline rocks, and gneiss. On the other hand, among the permeable class are gravel, sand, sandstone, most limestones, chalk, vesicular lavas, tuffs and scoria. The permeability of rocks on a large scale is much controlled by joints, and owing to abundance of joint-fissures many close-grained rocks, such as limestones, become actually very permeable.

The distribution and mutual relations of masses of permeable and impermeable rocks, stratified and unstratified, are the principal determining factors in the circulation of underground waters and the distribution of natural springs. They are also of great practical importance in choosing sites for artificial wells and borings. The principles involved can be best illustrated by a few examples.

The simplest case is where a tract of country consists of a mass of

[1] *Les Eaux souterraines*, Paris, 1887, vol. i. p. 7.

permeable strata overlying impermeable ones. Here the ground-water will accumulate in the lower part of the permeable rocks, and wherever denudation has trenched the land deeply enough to expose the junction of the two series, springs will issue (Fig. 35). The upper surface of the ground-water is found to be not horizontal, but to follow more or less closely the contour of the ground. This is due chiefly to the hindrances to free flow within the rocks themselves, owing to friction and capillarity.

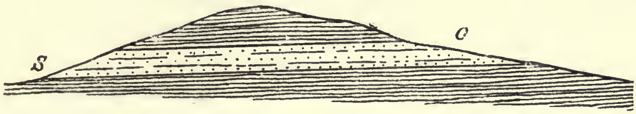


FIG. 36.
The spring, *S*, rises at a point far from the outcrop, *O*, which supplies it with water.

This state of affairs is well illustrated by some of the valleys in the Ingleton district in west Yorkshire, where porous Carboniferous Limestone rests on the massive slates and grits of the Silurian and older formations. On the limestone there is hardly any surface flow of water : all the rain sinks down joint-fissures and circulates underground. When it reaches the Palæozoic floor its farther descent is prevented, and copious springs issue on the sides of the valleys which have been eroded deeply enough to expose the older rocks. Although the actual junction is commonly

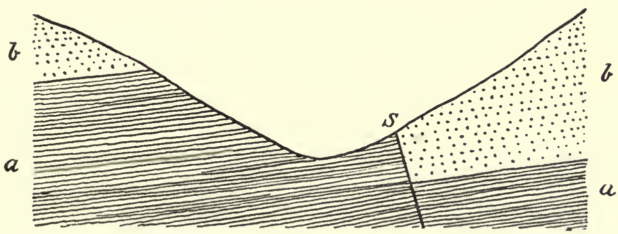


FIG. 37.—FORMATION OF A SPRING BY A FAULT.
a, Impervious ; *b*, Pervious strata ; *S*, Spring.

concealed by drift or alluvium, it can be followed on the ground with the greatest accuracy by means of the line of springs which issue from it. An almost exactly similar state of affairs exists in southern and eastern England, where the Chalk rests on the impervious clays of the Gault, or on the Chalk Marl, as in the neighbourhood of Cambridge.

If a pervious water-bearing stratum lies between two impervious ones, the water which falls upon the outcrop of the former will follow its underground course, and may issue as springs in a locality far removed from where it fell, as shown in Fig. 36. The number of possible variations of arrangement in connexion with water-bearing strata and springs of this kind is almost infinite, and no good purpose would be served by discussing them in detail. One important case, however, deserves mention, where the continuity of the strata is interrupted by a fault, so that a mass of impervious rock is brought up against a pervious one, as shown in Fig. 37. Here a kind of natural reservoir is formed, and springs will issue along the line of the fault.

Artesian Wells.—One of the most important questions connected with water-supply, both from the scientific and economic standpoint, is the possibility of obtaining water from deep strata. For all purposes this is much to be preferred to water from shallow wells and springs, owing to its freedom from contamination. The most favourable conditions for artesian wells and deep borings for water are found where a water-bearing stratum is enclosed between two impervious ones, and the whole gently folded into a synclinal form. The water which falls on the outcrop

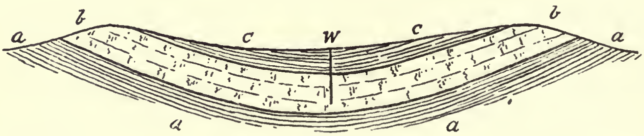


FIG. 38.—DIAGRAMMATIC SECTION ACROSS THE LONDON BASIN, SHOWING CONDITIONS FAVOURABLE FOR ARTESIAN WELLS.

a, *a*, Gault (impervious); *b*, *b*, Chalk (pervious); *c*, London Clay (impervious); *W*, Well.

of the pervious stratum runs into the synclinal basin, and is there stored under the pressure of a large head of water. Consequently, if the upper stratum is pierced by a boring, the water will be forced out under pressure, and may even form a jet issuing high above ground-level. These conditions are almost ideally realised in the London Basin (Fig. 38). The water-bearing stratum, the Chalk, lies between the London Clay above and the clays and marls of the Gault, &c., below. The Chalk has a wide exposure in the North Downs to the south, and the Chalk Hills of Bucks, Beds, Herts, and Cambs to the north. The rain which falls in these latter districts is nearly all absorbed, since there is hardly any surface drainage in Chalk districts; and it accumulates below London under a pressure equal to the weight of a column of water whose height is the difference in level between the tops of the Chalk Hills and the base of the London Clay. Of course, in reality the effective pressure is much less than this, being enormously reduced by friction; but still it is sufficient to cause the water to rise freely to the surface in such wells, or at least it did so in the case of the earlier ones. Owing to the increasing number of deep wells, pressure is now much reduced, and recourse must generally be had to pumping.

There exist in the town of Cambridge many deep wells, in which the general principle is the same as that just described. Here the water-bearing stratum is the Lower Greensand, which yields specially good water. Its outcrop is about four miles west of Cambridge, and the dip is very gently to the south-east, so that underneath the town the Lower Greensand lies at a depth of about 150 feet. It rests on the impervious clays of the Upper Jurassic, and is overlain by the equally impervious Gault. Consequently, if a well is sunk 150 feet or more, water will tend to rise in it. Here also, owing to the number of wells, the pressure is now much reduced.

Mineral Springs.—This term is applied in popular phraseology to springs which contain sufficient mineral matter in solution to give a distinct taste to the water. The term is therefore a very vague one, since a spring may hold in solution a large amount of a tasteless compound, such as calcium carbonate, and yet it would not be called a mineral spring, while the presence of a very small proportion of magnesium salts or sulphuretted hydrogen would give a very decided flavour to the water. The term is most commonly applied to such springs as have, or are believed to have, medicinal properties. Saline springs contain compounds, especially chlorides of sodium, potassium and magnesium; sulphur springs contain compounds of sulphur, especially sulphuretted hydrogen. This is usually derived from the decomposition of mineral sulphides in the rocks through which the water has flowed: some sulphur springs are of volcanic (solfataric) origin. Chalybeate springs are those which are rich in compounds of iron. Speaking generally, it may be said that the mineral constituents of spring water are derived by solution from the rocks through which the water has percolated, and its character naturally depends on the prevailing soluble compound in these rocks. Some springs issue at a temperature at or near that of the air; some are colder, especially when of fairly deep origin, while others are distinctly hotter than the air or ground temperature. Hot springs are known whose temperatures range up to boiling-point, and these are described in the chapter on Vulcanicity. The temperature of springs of deep origin is often very constant, being at or near the invariable ground temperature, so that they appear cool in summer and warm in winter.

Denudation in Desert Regions.—As is pointed out in another chapter of this book (Chapter I), a special type of denudation is to be seen in regions where the rainfall is small or completely deficient. Any large area in which the average rainfall is less than 10 inches per annum partakes more or less of the nature of what is popularly known as desert. The only important weathering agents in such regions are changes of temperature and strong solutions brought up by capillarity. These lead to a rapid and deep-seated breaking up of ocks, and provide vast quantities of dry, finely divided material to be acted on by agents of transport. Besides gravity, the only transporting agent of general importance is wind: water action is rare and local. It is true that on occasion great effects may be brought about by the sudden and violent rainstorms which are commonly spoken of as 'cloud-bursts,' but compared to the total amount of erosion these are probably insignificant, though occasionally very striking effects are produced over limited areas.

The study of desert erosion begins most conveniently with what are known as rock-deserts. These consist of great expanses of bare rock, usually of a mountainous nature, and here processes of denudation have full play. The sand formed by weathering is carried away by wind, and tends to accumulate at lower levels and to fill up inequalities in the ground, so that the final stage of such denudation is the production of a level plain. The higher ground is destroyed by erosion, and the hollows filled up by sedimentation, and after an intermediate stage of hill and valley we finally arrive at the vast, almost level, plain of sand, the popular idea of the desert.

It is in the intermediate stages of this process that the most interesting phenomena are observed. Chemical weathering often extends very deeply, and in an apparently capricious manner; it is facilitated by heavy dew, especially on the shady side of projecting rocks and cliff faces, and as a consequence curious hollows are produced, and a rock may sometimes be worn away to a mere shell. This kind of weathering, in conjunction with the scaling off of flakes from the surface (*desquamation* of Richthofen), often leads to very remarkable results. A mass of projecting rock is often weathered into the semblance of a wall with rows of windows and a continuous hollow passage behind, or rows of rock-pillars, columns and needles may be formed. All this appears to be due to intensive weathering along regular joint-planes. When this sort of action is combined with undercutting by blown sand very remarkable forms may be produced, such as mushroom-shaped rocks, often with a fringe of needles projecting downwards from their under surface.

The production of rock-pillars and mushroom rocks is not confined to desert regions. Even in England examples are known, such as the Brimham Rocks near Harrogate, the Hemlock Stone at Stapleford in Notts, and some very good examples in the Calcareous Grit of the East Yorkshire moors (Plate XI (i)).

On level ground there is often little or no evidence of a general lowering of the surface, except where there are alternate beds of hard and soft rock, such as limestone and shale. Channels are cut by weathering and the sand-blast along the joints of the limestone down into the shale (see

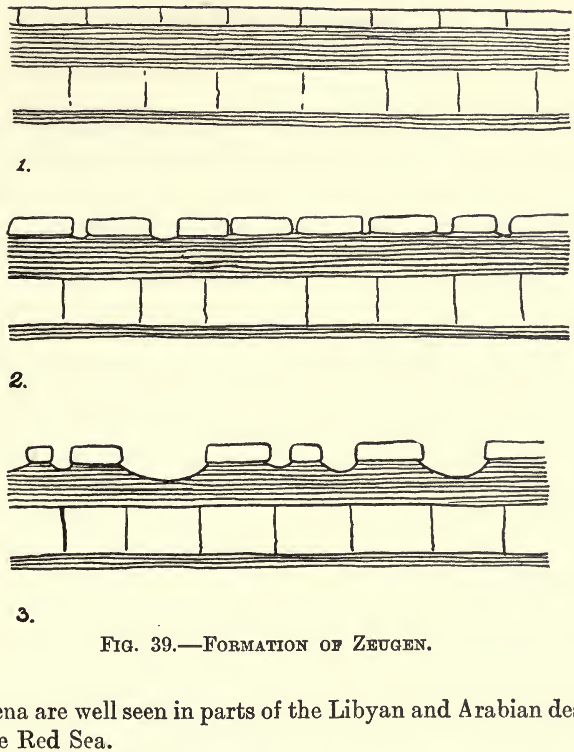
PLATE XI

Miss M. Keighley, photo.

(I) THE BRIDE STONE, NEAR PICKERING, YORKSHIRE.

(II) THE SPHINX, GHIZEH, EGYPT, SHOWING THE ORIGINAL FALSE BEDDING OF THE SANDSTONE AND THE ROUNDING AND ETCHING PRODUCED BY WIND-BLOWN SAND.

Fig. 39). These fissures are shaded, and chemical weathering proceeds freely, so that the limestone bed is undercut. Thus tables and pillars are formed with a cap of limestone on a support of shale. Eventually the caps fall off, and the shale is then rapidly weathered down to the next hard band, and so the whole process is repeated. These stratified masses projecting above the general plane-surface are called *Zeugen*, and they are found of all sizes, up to 100 feet or more in height. They have much in common with the Buttes of America. All these and similar



1.

2.

3.

FIG. 39.—FORMATION OF ZEUGEN.

phenomena are well seen in parts of the Libyan and Arabian deserts, and along the Red Sea.

The Sahara.—As an example of a typical desert we may take the Sahara. This area is by no means uniform, and a study of it by Zittel, Walther and others has led to a recognition of several more or less clearly defined types of desert topography. Contrary to the commonly received opinion, the Sahara is not a vast low-lying level plain or basin, but it is essentially a plateau or series of plateaux several hundreds, or even thousands, of feet above the sea, and only one or two very limited areas at the eastern end are below sea-level. There are one or two isolated mountain-chains composed of disturbed rocks, but almost the whole area consists of horizontal strata. The essential structure of the Sahara is that of a series of terraces or plateaux, rising one above the other and bounded by steep cliffs. These cliffs are a very prominent feature, and it is on them that the peculiar erosion-forms before described are specially developed. They are usually bordered by a conspicuous girdle of Zeugen of varying size, and they also show rock walls with windows, rows of pillars and other peculiar forms.

As regards the form and character of the ground, four chief types are recognised by Zittel—

1. Plateau desert, or Hamâda.
2. Erosion desert.
3. Sand desert.
4. Mountain desert.

Of these, the first is the most widespread. It is the desert in the true sense,—the hard, strong surface of a plain without noticeable elevations or depressions, without water or vegetation. The surface consists of bare rock or of hard loamy soil covered with rock-fragments.

The second division, or erosion desert, includes the most remarkable forms of weathering and erosion; it possesses a highly diversified surface, and includes the bounding walls of the plateaux with their Zeugen and Wadys. Besides valleys of the Wady type, which are more or less similar to ordinary river-valleys, there are also to be found great hollows, true rock-basins, which are often called *Schotts*. These are sometimes completely dry, and sometimes contain small salt lakes. When a certain amount of water is constantly to be found, and the ground is not too strongly impregnated with salt, these depressions form *oases* which are sometimes marvellously fertile. In many of them are copious springs, which issue at a high temperature, up to 105° F. The water from these springs is, however, all removed by evaporation, and transpiration of plants, and none of it reaches the sea. It appears that in many parts of the Sahara underground water is abundant; and new oases have been established in Southern Algeria by the French engineers, by means of deep borings and artesian wells, and much new ground has been brought under cultivation.

Sand or dune-deserts are the most desolate of all; they show a single vast sea of sand, of a white or yellowish colour, often mixed with gypsum. The surface is by no means level, but is broken up into great sand-dunes from 50 to 400 feet high, and sometimes between these the rocky floor is exposed. The structure and origin of sand-dunes is discussed elsewhere, under the heading of Terrestrial Deposits (see p. 80).

In the central and higher parts of the Sahara the Hamâda type passes into mountain desert: the highest plateaux reach as much as 6,000 feet above sea-level, and they are dissected by erosion into marvellously complex forms, which are of essentially the same type as those of the erosion deserts already described, but on a larger scale.

Wind Erosion and Transport.—After the rock-material has been disintegrated by weathering, in the manner previously described, by high temperatures and chemical action, the further processes of erosion are almost entirely performed by wind. It is true that there is occasionally, even in the driest climates, violent local action due to cloud-bursts and torrential rains, but, compared to the whole amount of denudation performed, this is insignificant. In the more hilly regions also, streams arise and carve out valleys for themselves for a certain distance, but they are soon lost by evaporation and the porosity of the ground.

Erosion by wind divides itself naturally into two parts—removal by material or *deflation*, which of course comes under the heading of transport, and actual corrasion or wearing away of the rocks by the dynamical effect of moving sand.

As above pointed out, deflation is the active agent or transport, and practically the only one; in conjunction with a special type of weathering, it is responsible for the peculiar relief of the desert. The action is very simple, so much so that there is really very little to be said about it: it simply consists in removal of loose material from exposed surfaces, its transport for a greater or less distance according to circumstances, and its final deposition, usually in a hollow or at a low level. In many regions wind-blown sand exists chiefly in the form of dunes or wave-like masses, whose form is determined chiefly by the effect of obstructions on air-currents. This subject is dealt with elsewhere.

Another point worthy of notice is that, unlike most agents of transport, wind can carry material uphill, and also across water-surfaces. Sand and dust from the Sahara is often carried by southerly winds into Sicily and other parts of Southern Europe. Very commonly also sand and dust are carried in large quantities into the salt lakes of desert regions and choke them up with deposits, which eventually solidify into sandstone and marl, and may frequently be interstratified with beds of rock-salt, gypsum and other soluble salts.

It appears that the maximum size of sand-grains which are commonly removed by ordinary winds is about 2 mm. in diameter, but during storms particles of much larger size are carried up into the air, and when they strike the surface of rocks they have very considerable energy.

However, according to the best authorities, erosion by blown sand is of much less importance than is commonly supposed. As compared with the effects of weathering and deflation, it is likened by Walther to a small decoration on the front of a great building. It is everywhere observable, but its power is much over-estimated.

The general effect of the *sand-blast* is to produce a conspicuous rounding and polishing of surfaces exposed to it. It brings out differences of hardness in stratified rocks, it digs out the felspar crystals from porphyritic lavas, and causes concretions and hard fossils to stand out as projections. However, in the case of fossils in particular, all finer details are generally lost, since the surface is usually much smoothed and rounded. Unlike glaciated rocks, wind-polished surfaces never show scratches (Plate XI (ii)). The effect of the sand-blast on exposed pebbles lying on the ground is peculiar; they are polished by the sand-blast and are word into smooth faces, which tend to enlarge and give a facetted appearance. These facetted faces eventually meet in straight edges, and from their prevailing three-cornered form these pebbles are known as *Dreikanter*. The edge between two facets is parallel to the direction of the air-currents along the ground, but does not necessarily coincide with the direction of the prevailing wind, as commonly stated, since local deviations may arise from many causes.

The occurrence of Dreikanter is of great geological importance, since in conjunction with wind-polish they form an indicator of the former existence of wind action.

Although its geological effects are small and rather superficial, the sand-blast is actually an agency of great power. Some instances of this are quoted by Walther: the telegraph wire on the Trans-Caspian railway had to be renewed after eleven years, as it had lost half its diameter by the action of blown sand, and on one occasion the sand-blast was sufficiently powerful to scrub all the paint off the locomotives on the same line of railway.

CHAPTER V

TERRESTRIAL DEPOSITS

THIS chapter will deal with the deposits which are now being formed on the land-surfaces of the globe, as the result of the working of the different geological agents whose modes of action have been described under the general headings of Denudation. As we have seen, the final resting-place of denuded material is the ocean-basins, where it is deposited to form the sedimentary rocks; but much of this material is not carried directly to the sea as soon as it is broken up by agents of weathering and denudation. Some of it finds a temporary resting-place in lakes, while some remains, for a time at any rate, on the surface of the land. It is with this that we have here to deal.

The character of such terrestrial accumulations naturally varies according to the physical conditions under which they were formed and the materials of which they are composed. A good deal of attention has been paid to this subject in America, and the following classification has been proposed by Merrill.[1] In this scheme no mention is made of soils in the ordinary sense of the word, since the soil is merely the superficial layer highly modified by the growth of vegetation. For the sum-total of all these terrestrial accumulations Merrill proposes the convenient term of *Regolith*.

Merrill's Classification of the Regolith.

Sedentary	Residual	Residual gravels, sands and clays, wacké, laterite, terra rossa, &c.
	Cumulose	Peat and swamp soils (in part).
Transported	Colluvial	Talus and cliff debris.
	Alluvial	Modern alluvium and swamp deposits, loess, &c. (in part).
	Æolian	Wind-blown sand, loess in part
	Glacial	Moraines, drumlins, eskers, &c.

[1] *Rocks, Rock-weathering and Soils*, 1897, p. 300.

The wording of this classification has been slightly modified by the omission of a few terms understood only in America. The terms in the second column mostly explain themselves; the only new words here are *cumulose*, which refers chiefly to accumulations of vegetable matter in situ, i.e. growth in place, and *colluvial* (derived from *colluvies*, a mixture), which signifies heterogeneous aggregates of rock debris derived from various sources, such as screes and mud-flows.

Residual Deposits.—Under this heading are included various deposits now covering the Earth's surface in places, and consisting of material which has been left behind during the ordinary processes of subaerial denudation. The mode of formation of residual deposits is fairly obvious, and scarcely needs detailed description. When a rock consisting of heterogeneous materials is weathered, some of its constituents are removed more easily than others; for example, nearly all soluble rocks, as limestone, contain more or less insoluble residue. In the case of a sandstone with calcareous cement, the latter is easily dissolved by water, and an aggregate of loose sand-grains left behind. The finer constituents of conglomerate may be washed away, leaving the pebbles behind, and so on. Thus are formed accumulations of clay, sand, gravel, &c., which are to be regarded as the residues of the rocks of which they once formed part. In the same way some of the constituents of igneous rocks are more easily removed than others, which are left behind, and often undergo marked chemical and physical changes. Evidently deposits of this kind show a close affinity to ordinary soils, from which they differ in many cases only by their greater thickness. In regions which have been recently glaciated such residual deposits do not generally show a great development, since sufficient time has not elapsed since the removal of all loose material by ice; and the formation of the heterogeneous accumulation of varying origin known as glacial drift is not residual, since it involved much transport. Residual deposits are best developed in regions covered by luxuriant vegetation, which prevents removal of weathered material. Consequently, in tropical regions the rock is often completely hidden by a great thickness of material of this kind, which is essentially soil above, graduating downwards into rotten rock.

As an example of residue from a limestone, mention may be made of the deposit known as *Terra Rossa*, a red ferruginous material which covers large areas on the limestones of the Adriatic region, and on the plateau of Franconia and Suabia. It is simply the insoluble residue of the limestone. With this may be compared the reddish soils which often cover the Carboniferous Limestone of the north of England and some of the Jurassic Limestones of the Midlands. The widely spread deposit known as Clay-with-flints in the south of England was formerly believed to be simply the insoluble residue from the Chalk, but

Mr. Jukes-Browne has recently advanced reasons for believing that some of the argillaceous Eocene beds have also taken part in its formation.[1] On some of the higher elevations of Cambridgeshire and Norfolk there are to be seen thick accumulations of gravel, chiefly flints, but containing also boulders of foreign rocks. These plateau gravels are believed to represent the heavy residue of the boulder-clay, from which the finer material has been removed by water action. At the foot of the South Downs, and especially in the neighbourhood of Brighton, there occurs a peculiar deposit which is known as the Elephant-bed, or more commonly as the Coombe Rock. It is a mass of angular flints and chalk, which show little signs of rolling by water action, and is entirely unstratified; the only organic remains are broken teeth of elephant and horse. For a long time the Coombe Rock was supposed to be a marine deposit formed by a temporary submergence, but all the evidence is against this view; and Clement Reid [2] has shown that it is in all probability an accumulation of material carried down from the higher parts of the Chalk downs at a time when the soil and subsoil was frozen to a considerable depth, so that rain was unable at once to sink in to the chalk as it does now, but formed rapid streams on a steeply inclined surface. The Coombe Rock is thus to be regarded as a torrential deposit formed during the prevalence of glacial conditions over Britain, but in a region which was not invaded by the ice-sheet. A somewhat similar accumulation, known as *Head*, is found in other parts of the south of England beyond the limits of glaciation.

Another important class of residual deposits includes those which are formed by alteration in place of rocks of igneous origin. Some of the more important of these are comprised under the general heading of *laterite;* and *bauxite*, the important ore of aluminium, is also to be included here. The origin of laterite has given rise to much discussion, but this at any rate is clear, that it arises by decomposition and weathering of basic igneous rocks, chiefly basalts. This change takes place especially in tropical regions, and the best-known development of laterite is in the basalt plateau region of the Deccan. It is a reddish, somewhat cellular clay, with ferruginous concretions, and it hardens considerably on exposure to the air. It consists largely of hydrated oxides of aluminium and iron with a variable percentage of silica, and some varieties with little silica approach closely in composition to bauxite.

In India two forms of laterite are commonly recognised: high-level laterite, which occurs on the elevated basalt plateaux, and low-level laterite, which occurs on the lowlands, and often overlies more acid rocks, granites and gneisses.

[1] *Q.J.G.S.*, 1906, p. 132. [2] *Q.J.G.S.*, 1887, p. 364.

It is not very clear why this substance is typically developed only in tropical regions, and it has been suggested that bacteria may play an important part in its formation.[1]

According to the latest views, it seems probable that the origin of bauxite is to be sought in a similar process occurring in volcanic rocks of acid composition.[2] The best-known occurrence of this mineral is in connexion with the Tertiary volcanic rocks of Antrim in Ireland, and the decomposition may have occurred while the climate was a good deal warmer than it is now.

Cumulose Deposits.—These for the most part consist of material which has actually grown in the situation in which it is now found. Consequently, they are chiefly of vegetable origin. By far the most important of them is the material comprised under the general designation of *peat*. This is a word of somewhat wide application, and it includes deposits of very varying origin and character, which only agree in consisting chiefly of partially decayed vegetable matter. Broadly speaking, these deposits can be divided into two classes—*Fen Peat* and *Hill Peat*. The former class includes accumulations of partially rotten vegetable matter, chiefly remains of rushes, sedges and other plants characteristic of lowland swamps, often with a good many remains of fresh-water mollusca, and frequently bones of animals. It is generally a very black muddy substance, without much structure.

This kind of peat is well developed in the Fenland of the east of England, where it includes buried forests, often to the number of four or five, one above another, and consisting of different kinds of trees. These are supposed to show variations of climate, and especially a change in the amount of rainfall.

Hill peat, on the other hand, is accumulated chiefly at high levels in moorland and mountainous country, and consequently consists of a very different assortment of plants. This subject has been exhaustively investigated by Lewis, who finds in the plant assemblages evidence of remarkable fluctuations of climate in Scotland and northern England in latest glacial and post-glacial times. Over almost the whole of Scotland, for example, there can be traced at least three arctic plant-beds, which alternate with forest beds containing plant remains of a much more temperate character. From the abundance of remains of trees in the forest beds, birch in the lower and pine in the upper, it is evident that at one time thick forests extended over Scotland and northern England nearly or quite to the tops of the highest mountains. Hill peat consists of remains of plants, of which mosses, and especially *Sphagnum*, are generally the most conspicuous; but it also includes all those species, such as heaths, dwarf willows &c., which characterise

[1] Holland, *Geol. Mag.*, 1903, p. 59; Maclaren, *Geol. Mag.*, 1906, p. 536.

[2] Grenville Cole, *Geol. Mag.*, 1908, p. 471.

PLATE XII

R. H. Rastall, photo.

(I) TORRENTIAL STREAM DEPOSIT. SEATHWAITE, CUMBERLAND.

R. H. Rastall, photo.

(II) ALLUVIAL FLAT, BETWEEN DERWENTWATER AND BASSENTHWAITE LAKE, CUMBERLAND.

the flora of elevated regions, including also a good many small flowering plants like Ranunculus, Potentilla, &c.

Colluvial Deposits.—This heading includes chiefly the piles of debris which are found at the foot of precipices and steep slopes generally, and commonly known in this country by the name of *scree.* We must also include here the material brought down by landslips, and the peculiar phenomena best described as *mud-flows.* It is unnecessary to enter into details of the formation of scree deposits: the subject has already been dealt with under the heading of Denudation. Screes are found in all mountain regions, and are specially well seen in the English Lake District. Mention may be made of the great Wastwater screes, and those on the west face of Skiddaw. The angle of inclination of a scree naturally depends on the nature of the material, but it rarely exceeds 30°. It is impossible to distinguish sharply between scree and landslips, which are connected by innumerable gradations. Sometimes in mountain regions accumulations of scree and other material lying on steep slopes become saturated with water and slide down bodily, forming *mud-flows.* A good example is the one which recently destroyed the railway between Visp and Zermatt, and dammed up the course of the river, forming a lake of considerable size. This is a common event in many mountain regions, and often occurs on a small scale in districts of quite low relief.

Alluvial Deposits.—This class includes a great variety of deposits whose essential character is that they were for the most part formed by water, chiefly by rivers. In consequence of this, they are nearly always more or less stratified. The most important alluvial deposits are those which are formed along the lower courses of rivers, where the current has become sluggish, and deltas are also to be included here. Large masses of alluvium are also to be found filling up old lake-basins at all elevations. This kind of alluvium usually graduates into peat. The source of such alluvial deposits is chiefly to be found in the finely divided material which is carried along in suspension by the waters of the rivers, especially during floods. When a river overflows its banks, the turbid waters spread in a thin sheet over the level ground bordering the river, and there deposit the fine silt which they contain. This silt usually gives rise to a soil of great richness, as in the case of the Nile, which contains abundant material derived from the decay of the crystalline rocks of Upper Egypt and Abyssinia.

Alluvial deposits vary a good deal in lithographical character, but on the whole they are chiefly fine sand or mud, usually containing also a good deal of organic matter derived from the decay of plants and animals.

The materials forming river deltas vary within somewhat wide limits, but they include perhaps a higher proportion of fine mud than the alluvium formed inland. This depends, however, very largely on the character of the country through which the stream has flowed. For example, the delta of the Nile is very largely composed of sand blown into the river from the desert on either side of its valley. The delta of the Mississippi is of a much more muddy character, and consists chiefly of fine silt and vegetable material.

Alluvial deposits are abundant along the courses of the meandering rivers of the south and east of England, which have long since established their base-line of erosion and are now engaged in cutting sideways and working over material already deposited by them. As is pointed out elsewhere, the Fenland is of a somewhat different character, and is not strictly river alluvium.

Æolian Deposits.—Wind as an agent of denudation has already been considered in Chapter I, but it is necessary here to give some account of the character of the deposits in whose formation wind plays the chief part. Æolian deposits are most largely developed in those arid regions popularly known as deserts, but they also play an important rôle in some temperate regions, as sand-dunes, steppe-deposits and loess. It will be necessary to treat æolian deposits in somewhat greater detail than the classes of terrestrial accumulations just considered, since they form a peculiar and characteristic type of sedimentation which is largely developed both at the present day and in the older formations.

The special character of the dry weathering of desert regions has already been described, and it was pointed out that the disintegration of the rocks is almost entirely due to the effects of strong solutions and high temperatures. These lead to a rapid and deep breaking up of the rocks, and provide vast quantities of dry, finely divided material to be acted on by agents of transport. Besides gravity, the only transporting agent which is of any importance is wind: water action is rare and local.

A great part of the Sahara and other extensive deserts consists of a vast sea of sand of a white or yellow colour, often mixed with gypsum. The surface is by no means level, but is broken up into great sand-dunes from 50 to 400 feet high, like petrified waves; sometimes between these the rocky floor is exposed. These dunes appear to be a permanent feature of the landscape: when once formed they remain fixed in the same position and do not possess a movement of translation, like the sand-hills of more northerly regions. Wind action is very powerful, and during a sand-storm, or *Samum*, there is great transfer of material from one dune to another, but their positions as a whole remain the same. The reason for this is that their place is determined once for all by some irregularity of the surface, and it is only under exceptional circumstances that changes are produced. Sometimes, however, a chance obstacle, even a dead camel, is sufficient to cause an accumulation of sand during a storm, giving rise to a new dune. All the groups of dunes along the caravan routes possess names, and are well known to the natives as permanent features.

Individual dunes show a gentle slope on the windward side, and a very steep slope to leeward, due to eddies in the air-currents, which have a sort of scooping action behind their crest[1] (Fig. 40). Their surface is often diversified by minor ripples. The steep slopes on the leeward side form a great hindrance to travel, and caravans often have to travel along the foot for a great distance before a chance depression allows them to cross over into the next valley. As a rule the distance from the crest of the wave varies from half a mile to a mile in the open desert.

Form and Arrangement of Sand-dunes.—Since the piling up of sand into dunes is wholly due to the action of the wind, their form and arrangement is controlled by the direction and intensity of the prevailing winds of the district. When the sand is merely heaped up into mounds, these are often arranged in rows either parallel to the

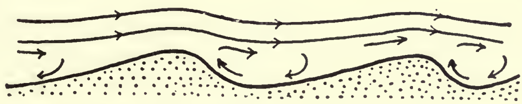


FIG. 40.—DIAGRAM TO SHOW THE FORMATION OF SAND-DUNES.

The direction of the air-currents is shown by the barbed lines. (After Vaughan Cornish.)

wind or at right angles to it. When it takes the form of long narrow ridges, true dunes, the arrangement of these follows the same law; the parallel or transverse character of the ridges depends on the relation between the supply of sand and the average strength of the wind. In North-western India the prevailing winds are from the south-west, and the supply of sand comes from the same direction. Near the coast the ridges are parallel to the direction of the wind, while in the interior they are transverse to it, and this seems to depend on diminishing strength of wind at a distance from the coast. In the deserts of Central Asia the sand is often piled up into peculiar crescent-shaped forms with their convex sides facing the wind. In regions where the wind is variable in direction this regularity of arrangement is naturally destroyed, and the sand is merely piled up into confused heaps of no definite form and arrangement; and similarly the ideal symmetry of a dune with its steep leeward and gentle windward slopes is also obliterated by changes of wind.

[1] Vaughan Cornish, *Geographical Journal*, vol. ix., 1897, p. 278.

Sand-dunes and Sand-hills.—In many temperate regions there are to be found along the coasts great accumulations of blown sand. These are of essentially the same character as the sand-dunes of the desert, but they differ in this respect, that the sand is mostly prepared by marine erosion, and not by dry weathering. Consequently, sand-hills are most conspicuous along coasts which are greatly exposed to the prevailing winds of the region. In Europe, therefore, accumulations of blown sand are most noteworthy on coasts much exposed to westerly and south-westerly winds, such as Devonshire, Wales and Cumberland, some parts of the west of Scotland, and the French coast of the Bay of Biscay. They are also found to a less extent on the eastern coasts of Scotland and England, where easterly winds are prevalent. The mode of formation of these accumulations is very simple: the sand is prepared on and near the beach by wave-action, cast up by the waves and carried inland by the wind; and the formation of the sand-dunes follows much the same laws as in desert regions, except that they are not stationary, but in a continual state of movement, often rapid, so that new tracts of country are continually being overwhelmed by them.[1]

The Loess.—One of the most remarkable terrestrial accumulations is the Loess, which covers enormous areas in Europe and Asia, while a very similar deposit is known in America as *Adobe*. It seems probable that under the designation of loess there are included deposits of more than one origin. The classical description of the loess is that by Richthofen[2] in China; and this author regards it as largely an æolian deposit, due to the action of wind transporting fine detritus into enclosed basins, where it is ultimately deposited among growing vegetation. The origin of this fine dust is somewhat obscure; but it has been suggested that it represents the mud left behind by the fluvio-glacial drainage of the Glacial period, and subsequently desiccated during a time of dry climate, which appears from other evidence to have succeeded or caused the disappearance of the ice. As seen in China, the loess is a fine calcareous clay or loam of a yellowish or buff colour, quite soft, but still possessing the peculiar property of resisting weathering agents, so that when cut by streams it stands up with vertical walls to a great height. Hence deep gorges abound, and in the sides of these cliffs cave-dwellings are excavated by the inhabitants. One of the most remarkable features of the loess is the presence of innumerable vertical tubes of very small diameter, and lined with a layer of calcium carbonate, which are commonly assumed to be due to fine rootlets. It is entirely unstratified, and very uniform in character.

The loess extends from the extreme north of France through Belgium

[1] Walther, *Das Gesetz der Wüstenbildung*, Berlin, 1900, chapter xi.

[2] Richthofen, *Geol. Mag.*, 1882, p. 293; also *China*, Berlin, 1877–85.

and Germany, over the plains of Poland and Russia, and in the Carpathians it reaches a height of 5,000 feet above sea-level. It covers an enormous area in Central Asia and China, where it appears to reach a depth of many hundreds of feet. A similar deposit covers thousands of square miles in the Mississippi basin. The Adobe of North America is a very fine-grained calcareous clay, which possesses many of the same characteristics as the loess: it forms the soil of a large portion of the rainless area of the United States and in Mexico. It seems to reach a depth of two or three thousand feet, and in some cases has partially buried mountains, whose crests still project above it.

CHAPTER VI

SNOW AND ICE AS AGENTS OF DENUDATION

Formation of Snow and Ice.—In the previous section we have studied in detail the geological activity of water in the liquid state: it is now necessary to consider in a similar manner the effects of water when it exists in the solid form, as snow and ice. Under the ordinary atmospheric pressure the transition of pure water from the liquid to the solid state occurs when the temperature of the water is 0° on the centigrade scale. In many parts of the world the temperature of the air frequently falls below this limit, and as a consequence water is solidified. The surface water of the land, in rivers and lakes, freezes to ice, and sometimes the sea also, although the freezing-point of salt water is much lower than that of fresh. Again, the aqueous vapour of the atmosphere, when condensed at a temperature below freezing-point, falls as snow or hail.

The occurrence of low temperatures under natural conditions depends upon several factors, of which the chief are latitude and elevation above sea-level. It is well known to everyone that the climate becomes progressively colder from the equator towards the poles, and also as we ascend above sea-level; and it is unnecessary to discuss the cosmical and meteorological causes of these phenomena. Geology is concerned solely with the results, which are of extreme importance.

To study in full completeness the geological effects of low temperatures we must turn to the polar regions, where they occur on the largest scale. However, many of the fundamental facts have been ascertained from an examination of the phenomena displayed in mountain regions in lower latitudes, and in particular those of the Alps.

Cause of Glacial Conditions.—It is well known that in all parts of the world, at a certain variable height above sea-level, the mean annual temperature of the year is at or below freezing-point, and this condition favours the accumulation of ice and snow; but this is not the sole, or even perhaps the principal, determining factor. The necessary condition for the existence of perpetual ice and snow is that the amount formed during the cold season shall be greater than the amount removed by melting during the warmer period. Given a sufficiently low temperature, the lower limit of the snow is obviously the level at which there is equilibrium between the snowfall of winter and the melting of summer ; above this line there must be accumulation of snow, unless this is compensated for by an actual transfer of material from a higher to a lower level, and this compensation is as a rule effected by the movement of glaciers, which often extend, as rivers of ice, far below the normal snow-line. This is possible because material is carried down faster than it can be removed by melting. It follows from this that the lower limit of an ice-stream is rarely stationary for any length of time. It is generally either advancing or retreating. If the supply from above is checked while melting is still going on below at the same rate, the front of the ice will retreat, although the stream may actually be moving downwards.

It is evident, therefore, that one of the necessary conditions for the existence of perpetual ice and snow, apart from temperature, is a sufficiently large precipitation. The coldest region of the globe appears to be Eastern Siberia ; but here the surface of the ground is not permanently snow-covered, because the snowfall of winter is comparatively small, and the heat of summer is sufficient to melt it. In Greenland, however, although the mean annual temperature is much higher, there is an enormous accumulation of ice and snow, because this region is well within the reach of the moisture-laden winds from the Atlantic, and the snowfall is very great. In the Antarctic also similar conditions exist, but this region is at present much less known.

One of the most important facts established by the study of glacial geology is the former existence of glaciers and their accompanying phenomena on the largest scale in regions which now enjoy very different climatic conditions, such as parts of North-western Europe, including the British Isles, and eastern North America; while on the other hand the study of these vanished glaciations has thrown much light in its turn on some of the obscure phenomena of the present day in other regions where glacial conditions now prevail.

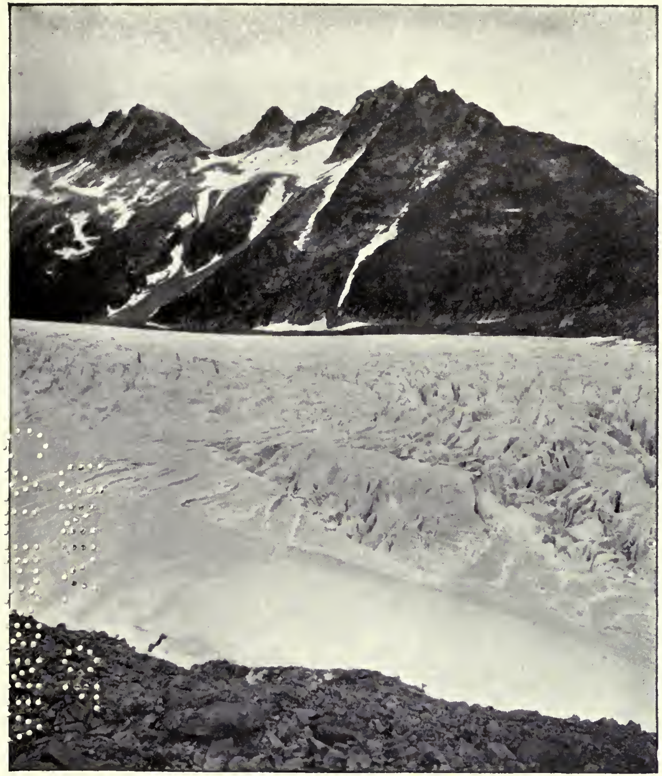
Snow-fields and Glaciers.—In regions of heavy precipitation, above the snow-line snow accumulates to a great depth, especially on plateaux and in the valleys. The pressure of the overlying layers consolidates the under parts into a firm, more or less coherent, mass. This kind of ice derived from snow is called in the Alps *névé* or *Firn*, and these terms are now in general use in other districts. As this *névé* accumulates it begins to move downwards, and forms what are commonly spoken of as glaciers. Although ice, regarded in small masses, is a very brittle solid, yet in bulk it possesses some of the properties of a viscous fluid, since it is able to flow; and in many ways the behaviour of glaciers presents certain analogies to that of rivers, and they may be conveniently regarded as rivers of ice. There has been much controversy as to the mechanics of the movement of glaciers, and the question is still far from settled. The subject will be dealt with in a later section (see p. 97), after some actual examples have been described. Ice which is formed from snow by pressure possesses some peculiar characters, which serve at once to distinguish it from ice which is formed directly by the freezing of water on the surface of lakes, rivers, or the sea. In a few cases, again, considerable masses of ice are formed by the freezing of the lower layers of masses of water in contact with a cold floor. This *ground-ice* is only of importance in arctic or sub-arctic regions, where, however, it often occurs on a considerable scale.

Avalanches.—Where snow accumulates to a great depth in mountain regions, where steep slopes are common, it often falls in large masses by its own weight. Such snowfalls are known in the Alps as *avalanches* or *Lawinen*. They have been exhaustively studied by Heim and others, and several types have been distinguished. Primarily they may be divided into ice-avalanches and snow-avalanches, and the latter alone are of much importance. It is often assumed that avalanches are of exceptional occurrence, and necessarily very destructive, but this is by no means the case. Avalanches are a perfectly normal and regularly occurring phenomenon over the whole region of the Alps, and they also occur in all other snow-clad mountain-ranges. In many localities an avalanche is a regular yearly occurrence, which takes place at a more or less definite time, and in some cases it has been observed that the avalanches from the different parts of a given mountain mass fall yearly in a fixed order. Like glaciers, avalanches have their own gathering-ground, their well-defined track, and their place of melting. They often bring down considerable quantities of rock-material, and their path is often scratched and more or less polished. When left behind on the melting of the snow, this rocky material looks much like the deposits of glaciers.

In the Alps avalanches most commonly originate at a height somewhere between 6,000 and 8,000 feet, where the yearly snowfall usually amounts to about five metres. There are two types of snow-avalanches, which are called in Switzerland *Staublawinen* and *Grundlawinen*.

Staublawinen occur in the coldest weather in winter, and consist of dry, powdery, newly fallen snow, which will not cohere, and often slips bodily off an inclined surface of older snow. The dry snow rises in the air like a cloud as it falls, and causes a strong wind-blast to arise, following the course of the snow. This wind often does more damage to the buildings and trees in the valleys below than the snow itself, since it travels farther.

Grundlawinen occur in spring, during thaw-weather, especially after a sudden rise of temperature. At this time the snow is wet,



J. J. Lister, photo.

(I) CREVASSES IN THE RHONE GLACIER APPROACHING THE ICE-FALL.

J. J. Lister, photo.

(II) FIESCHER GLACIER, FROM THE PATH TO THE MÄRJELEN SEE.

heavy and adhesive, and melts from below ; this produces hollows, and often causes it to slip off steep surfaces. The movement is a complex mixture of flowing, rolling, sliding and falling, and when it stops the whole mass is almost instantly solidified by regelation. The wind-action here is inconspicuous.

When the snow is in a condition of nicely balanced equilibrium an avalanche is often started by some very trifling disturbance, such as an incautious footstep.

Glaciers.—In most cases, however, the removal of snow from a higher to a lower level is not the sudden process outlined in the last paragraph, but of a much slower nature. As before pointed out, the snow is consolidated into ice, and moves downwards in this form, in a gradual manner, producing ice-streams or glaciers. Glaciers in the ordinary sense are found in most high mountain regions, even in tropical latitudes where the elevation is great enough. Their scientific study originated in the Alps, and has now been extended to many other parts of the world. The terminology employed in describing the various features of glaciers is mostly, therefore, of Swiss origin, being derived from the local dialects of the Alpine region.

Glaciers of the Alps.—In the higher parts of the Alps glaciers are very abundant, although none of them reach the great dimensions of those of some other regions. In all there have been enumerated some 1,200 permanent and independent masses of ice, but only about 250 of these are glaciers of the first order. A large proportion of the remainder are mere accumulations of snow in hollows, which scarcely merit the name. It is obviously impossible to draw any definite distinction between a true glacier and a snow-field, since one merges into the other, and the upper part of a true glacier is always a snow-field.

A large glacier may usually be divided more or less definitely into two regions—an upper one composed of névé or firn, and a lower one of ice ; the limit between the two, where the snow changes to ice, is often spoken of as the *Firn-line*, but this of course applies to the surface only, since the lower layers above this line are consolidated by pressure. It is to be noted that this firn-line does not necessarily coincide with the snow-line on the rocky parts of the adjoining mountains ; for example, in the Finsteraar district the firn-line is some 650 feet lower than the snow-line. This difference is due to the movement of the glacier. The mass of ice below this firn-line is commonly regarded as the true glacier. It appears, therefore, that in the firn region precipitation is in excess, and below it, melting. The firn-line represents the condition of equilibrium between the two.

The upper part of a glacier-basin, then, is filled with coarsely granular ice, the firn or névé. These névé-fields are not generally simple, except in the case of the smaller glaciers, but they usually comprise several tributary valleys, as in the case of the well-known Aletsch glacier, and most of the other large glaciers of the Alps. The Mer de Glace consists of three main streams, each of which is again made up of tributary branches. The glaciers of the Alps very rarely branch downwards, though this is common in high northern latitudes. Owing to the configuration of the ground in the Alps, i.e. sharp peaks and ridges, without high plateaux of large extent, several glaciers never radiate from a common snow-field, as they do in Norway, Spitsbergen and elsewhere. Hence simple, independent glaciers of this kind are distinguished as the *Alpine* type.

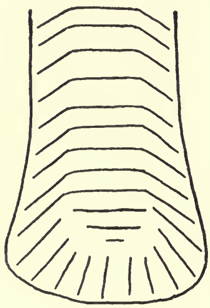


Fig. 41.—Crevasses in the Rhone Glacier.

In the middle, transverse; near the edges, directed downwards and outwards.

Characters of Alpine Glaciers.—Turning now to a consideration of the ice-stream, the glacier proper, we find that its surface is not perfectly smooth, but is diversified by various features. The glacier rests on an uneven floor, and this unevenness is the cause of inequalities at the surface. Sometimes the glacier falls over a steep slope, forming an ice-fall, analogous to a water-fall. This causes tension, and results in the formation of transverse cracks of varying width, called *crevasses*, which are often of great depth (Plate XIII (i)). Again, since the ice behaves more or less like a viscous fluid, it obeys the ordinary laws regulating the flow of streams, and the centre flows more quickly than the sides; this results in the formation of crevasses, starting from near the sides and pointing upstream (see Fig. 41). Sometimes also longitudinal crevasses are formed, and the diagonal crevasses may be regarded as the resultants of combined transverse and longitudinal strains. Since the superficial parts of a stream flow more rapidly than the under parts, there must also be differential movement between different layers in the ice, resulting in shearing strains, which often set up foliation in the ice.

In a few cases ice-falls are developed to such an extent in the course of a glacier that there is an actual discontinuity; that is to say, the ice-stream falls bodily over a cliff and collects in a pile at the bottom. Owing to melting and refreezing, this mass of ice cements itself again into a solid stream and continues on its way: such are spoken of as *regenerated glaciers*.

Moraines.—Glaciers of the Alpine type, surrounded by considerable areas of bare rock which are constantly undergoing denudation, collect in their course a good deal of rock waste, which at first at any rate is carried on the surface of the ice, and forms what is called in the Alps *moraine.* There is a good deal of confusion as to the use of this term in geological literature, as it is applied indiscriminately both to the rock waste carried on the surface and to the piles of rubbish deposited at the melting end of the glacier, much of which is derived from the floor and sides of the valley, below the level of the ice.

Most of this rock waste from the surrounding peaks naturally falls at or near the side of the glacier, and is carried on as a marginal stream: this is called *lateral moraine.* When two glaciers coalesce, the two lateral moraines on the inner sides unite and form a central or *medial moraine.* In highly complex glaciers, such as the Aletsch, numerous medial moraines can be distinguished following the windings of the stream, and each formed by the union of two tributary glaciers. (See Pl. XIII (ii)).

As the moraine material travels onwards, part of it is frequently swallowed up in the crevasses, and is thus carried down to a lower level, or even to the sole of the glacier, where it is mixed up with the material derived from the floor, both together forming the so-called *ground-moraine.* As the ice melts in its descent, moraine material becomes more and more concentrated; and finally the whole is deposited at the end of the glacier, forming a *terminal moraine*, which is usually a more or less well-defined ridge, whose form, however, depends on the configuration of the ground.

Drainage of Glaciers.—During the summer months, and at other times when the temperature is sufficiently high, a good deal of surface melting goes on, and this often produces a considerable amount of surface drainage. This water falls down any crevasses which it may encounter, and works its way down, forming a system of streams within the ice. This kind of drainage is now generally known as *en-glacial*, in contradistinction to *sub glacial*, which refers to drainage running on the rocky floor below the ice, and not enclosed within it. En-glacial streams seem to play a more important part in the glaciation of the high north, and will be more fully discussed in a subsequent section. The drainage of the glacier runs out in a stream at the lower end, often from a tunnel in the ice. The water is commonly more or less turbid or milky owing to the large amount of finely divided material, or rock flour, suspended in it.

Distribution of Glaciers of the Alpine Type.—Glaciers of the type here described occur in many other mountain regions besides the Alps, e.g. in the Himalayas, Andes, Rocky Mountains, and New Zealand; but they are not universal in all mountains which rise above the snow-line. In some cases, and especially on isolated peaks, no true glaciers occur, since the topography is unfavourable. For the proper development of a glacier something in the nature of a gathering-ground must exist;

and this need can only be supplied by the occurrence of well-marked valleys and hollows among the peaks, such as are found in perfection in the Alps, but are scarce or wanting in many simple cones, such as Ararat, and many of the great volcanoes of the world. Sometimes in extinct or dormant volcanoes great accumulations of snow and ice are found within the craters: this appears to be the case in some of the higher Andes.

Glaciation of the Arctic Regions.—Although the glaciers of the Alps appear to be a sufficiently striking feature, yet they are almost insignificant in comparison with the great ice-masses of polar lands, and it is quite clear that they are now mere shrunken remnants of a once far greater system which extended far and wide over the lower regions round. Of recent years the greatest progress in the study of glaciation has been made in high latitudes, especially in Spitsbergen, Greenland, Alaska, and in the Antarctic. Here the phenomena in question are exhibited on the largest scale, and from them it has been found possible to make generalisations which are unattainable in the more limited area of the Alps, and we must now turn to a somewhat detailed consideration of the regions in question.

The Glaciation of Spitsbergen.—During recent years a good deal of attention has been paid to the glacial phenomena exhibited in the high arctic archipelago of Spitsbergen. This group of islands lies close to the 80th parallel of north latitude, in a region of heavy precipitation, and its topography favours the accumulation of snow-fields on a large scale.

The dominant feature in Spitsbergen is the existence of great central névé-fields, lying on high plateaux, from which several ice-streams radiate in different directions towards the sea. This forms a second type of glaciation, in contradistinction to the Alpine type, in which each névé-field terminates in a single ice-stream. This is described by Heim [1] as the Norwegian type of glacier, since it is also well seen in the Scandinavian peninsula, and it may be regarded as specially characteristic of high plateaux with broad surfaces of small relief.

A detailed description of the glaciation of Spitsbergen has been given by Professors Garwood and Gregory,[2] and what follows has been abstracted from their papers. There are three main snow-fields, which are spoken of by these authors as 'inland ice-sheets.' This term as here used is synonymous with the 'ice-cap' of most writers, hence some confusion has arisen. From these great snow-fields glaciers extend down the valleys; on the whole, each of these is very similar to a Swiss glacier, but there are certain important differences. Most of the glaciers of the

[1] *Handbuch der Gletscherkunde*, p. 50.

[2] *Q.J.G.S.*, 1898, p. 197; also Garwood, *Q.J.G.S.*, 1899, p. 681.

J. J. Lister, photo.

(I) ICE CAVE AT END OF FEE GLACIER, SWITZERLAND.

J. J. Lister, photo.

(II) CRESCENTIC TERMINAL MOUND OF THE OBERAAR GLACIER.

J. J. Lister, photo.

(I) ALETSCH GLACIER FROM THE EWIGSCHNEEFELD.

F. H. Hatch, photo.

(II) GLACIATED PAVEMENT WITH DWYKA CONGLOMERATE RESTING UPON IT. MHLOGANYATI SPRUIT, NATAL.

Alps have rounded or sloping terminations, but in Spitsbergen the majority end in a vertical or overhanging front. This kind of termination is described in Greenland as a 'Chinese wall.' It is found in Spitsbergen that those glaciers with a Chinese wall front are advancing, while the others are retreating. The steep front is due to the more rapid movement of the upper layers, whereas in the retreating glaciers this is compensated for by the excess of melting. However, both types often exist in close proximity, as in the case of the Booming and Baldhead glaciers, so possibly some other factor is involved. There are in Spitsbergen also small glaciers of Alpine type, which as a rule have no snow-field at the head, so that it appears that under Arctic conditions snow may be converted directly into ice without pressure, and the existence of glaciers does not necessarily postulate great snow-fields.

Included rock-material is extremely abundant, especially in the lower layers, and it is impossible to draw any hard-and-fast line between the ice and the underlying floor ; the so-called ground-moraine is really the lowest layers of the ice, and this ground-up material is exactly similar to much of the 'boulder clay' of the British Isles and elsewhere. This material is clearly laid down by the glacier, but is deposited along its whole length, and not as a sort of tip-heap at the end, as is often inferred.

The Glaciation of Greenland.—The most extensive development to glacial conditions in the northern hemisphere is that which occurs in Greenland.[1] This has been investigated in much detail of late years, and these researches have thrown much light on the conditions which must have occurred both in Europe and America during the Glacial period.

The glaciation of Greenland does not differ in any essential respect from that of Spitsbergen ; it consists of a great central ice-cap from which glaciers radiate to the sea, but here the ice-cap is much larger in proportion to its off-shoots, and is usually designated as an *ice-sheet.*

The Greenland ice-field, according to Chamberlin,[2] extends over more than 20° of latitude, from 60° to beyond 82° N., and it has a width of several hundred miles. Its total area is estimated by the Danish explorers as nearly half a million square miles. Some of the islands off the coast also possess an independent system of glaciation. For example, on Disko Island the ground above the 2,500 feet contour-line is covered by an ice-cap of the Spitsbergen type, from which tongues of ice descend in cataracts over the well-bedded rocks into the fjords of the coast.

On the mainland to the north of Disko, the central ice-sheet comes down to sea-level and forms ice-cliffs of great extent, from which

[1] Rink, *Scottish Geogr. Mag.*, vol. v., 1889, p. 18.

[2] *Journ. Geol.*, vol. ii., 1894, p. 649.

numerous icebergs are given off. A good locality in which to study the central ice-mass is afforded by the neighbourhood of Inglefield Gulf. which is probably the region of greatest extension of the ice. The land here takes the form of a non-mountainous plateau, about 2,000 feet high, and the edge of this is notched by valleys down which the ice-streams reach the sea. The Igloodahomyne glacier is such a tongue of the great ice-cap, some three miles in length; its termination is steep, but not vertical, and it shows no terminal moraine. In the glaciers of Greenland the prevailing type of front is the Chinese wall, which has already been described.

The inland ice of Greenland, apart from the coast glaciers, has been exhaustively studied by Drygalski and by the Danish observers. According to the latter, it is a vast plateau of ice and snow, sloping uniformly away from the axis of the country; the mean slope varies from 50′ to 2° 14′, and is slightly steeper on the west than on the east. The greatest height attained by Nansen in his journey across the country was about 9,000 feet. No rock has ever been observed projecting through the ice at a greater distance than about seventy-five miles from the coast, and as a consequence the surface in the central parts is entirely free from debris of any sort. The surface is formed of powdery snow, but at a small depth this is consolidated into ice.

Nunataks.—The most interesting features are to be observed in the neighbourhood of the coast, where alone it is possible to study the relation of the ice to the underlying rocks. Within the coastal belt rocky peaks project as islands from the ice, and to these the Eskimos give the name of *Nunataks*. Some of these nunataks have been studied in detail by Drygalski and by the Danish observers, and the phenomena which occur at and around them help us greatly in understanding the movements both of the ice itself and of the solid material contained in it. It is found that in these regions the movement of the ice is very serpentine, and much influenced by obstacles. These set up strains, which produce many crevasses; the crevasses may be either transverse or longitudinal, or radial where the ice spreads out like a fan, after squeezing through a narrow gap.

The Karajak Nunatak, described by Drygalski,[1] is a narrow ridge some twelve miles long by three miles broad, running in a N.N.E.-S.S.W. direction, and bordered on its western side by a fjord. It comprises many peaks; and there are numerous lakes, some in true rock-basins on the nunatak itself, others marginal, bounded on one side by rock and on the other by ice.

Jensen's Nunataks[2] are a group of mountain-peaks some 5,000 feet

[1] *Grönland Expedition*, Berlin, 1897, chap. iii., p. 48.

[2] *Meddelelser om Grönland*, 1879, vol. i. Map C, Plate V, *C*, *C″* and *C‴*.

above sea-level, rising far out on the inland ice-field, and projecting only a few hundred feet at most above its surface. This barrier diverts the ice from its usual south-west course and forces it to travel round the northern and southern ends of the group. There are also two wide passages between the peaks, across which some ice finds its way. On account of the pressure behind it the ice rises much higher on the north-east side of the nunataks than on the south-west, where indeed there are distinct hollows; and in one of these is a nearly circular lake about 300 yards in diameter and 4,000 feet above sea-level, while the surface of the ice on the sides of the basin is some 800 feet higher. One nunatak does not quite reach the general surface of the ice, but its peak is to be seen at the bottom of a hollow in the ice.

Moraines in Greenland.—The most striking feature of this group is the manner in which moraine-material occurs around it. The ice, near its contact with the rock, is seen to be full of rock-debris, and this is thrown up against the margins of the nunataks into moraines. These frequently form crescent-shaped ridges [1] on the side from which the pressure comes, and it is clear that this forms part of the ground-moraine of the ice-sheet, which has worked up to the surface along the slopes of the buried peaks. It is thus clear that an ice-sheet can carry material uphill. Along the west or lee side of the group are other moraine ridges, one of which is three miles long and 400 feet high.

In Greenland moraines only occur close to rocks in situ, either those of the coast or nunataks. There are only one or two doubtful exceptions to this rule, and in these cases buried peaks are probably covered by a small thickness of ice.

Two types of moraine can be distinguished in Greenland: ground-moraine, which occurs at the ends of the ice-streams or glaciers proper, in the valleys leading to the coast; and marginal moraines, which occur along the edges of the ice; when very thick, up to 100 feet or more, these indicate a former higher level of the ice. Both types consist for the most part of large and small stones with rounded corners, and commonly well scratched. There is also a small amount of interstitial material of a clayey nature.

Characters of the Ice.—As regards the character of the surface, the line of division between the inland ice and the ice-streams is not clearly marked. The surface is usually much fissured, and these fissures run in directions determined by the prevailing stresses. At certain times of the year there is a good deal of melting on the surface, and this water soon runs into fissures and often widens them. This surface-melting is only active from June to September; during the rest of the year there is no superficial drainage, since the air temperature is below

[1] *Loc. cit.*, Plate V, *D′*, and *D″*.

freezing-point. Dust or pebbles lying on the surface absorb heat more strongly owing to their dark colour, thus tending to melt the ice below them, and consequently they sink into the ice, forming little hollows. Pebbles are often found at the bottom of holes several inches deep.

The colour of the ice is not uniform, but it is differentiated into blue and white bands, which run in a direction perpendicular to the surface and transverse to the direction of flow. These vary in thickness up to one or two inches, and they are generally lenticular in form. The colour of the blue bands is due to clearness of the ice and absence of air-bubbles, which are very abundant in the opaque white bands. Besides this colour-banding, the ice always seems to possess distinct lamination, which is usually parallel to the base, but often more or less contorted. Sometimes this lamination consists, near the base, of an interstratification of layers of sand and gravel with the ice. Sometimes the structure looks like foliation rather than bedding, and in this case it is probably due to shearing.

When the end of a glacier can be seen, it is nearly always observed that the lower layers are dark in colour and full of debris, while the upper part is pure ice. It has been suggested that this may, in part at any rate, explain the origin of the Chinese wall front, since the dark portion will melt more quickly owing to its greater power of absorption and so cause the upper part to overhang; but this explanation seems inadequate to account for all the facts observed.

Tide-water Glaciers.—On many parts of the Greenland coast, and especially towards the north, long tongues of ice come down from the inland ice-sheet and reach the sea. Since the movement of the ice is here very rapid, large masses become detached and float away as icebergs. One of the best examples is afforded by the great Humboldt glacier. This forms a range of ice-cliffs which is said to be forty miles in length and as much as 300 feet in height, with a precipitous or overhanging front. This latter is a common feature of all the tide-water glaciers of the north. Several very large glaciers of the same type were found by Nansen on the east coast, and indeed they are a common feature of this region. Along the east coast there is such an accumulation of icebergs, owing to a shoal, that access is almost impossible, and this part of Greenland has hardly been explored. It is a very remarkable fact that in the extreme north of the country, so far as it is known, glaciers are much less developed, and they do not generally seem to reach sea-level. This is probably owing to smaller snowfall on the leeward side of the great continental mass, which deprives the Atlantic winds of their moisture.

Alaska.—The glaciation of Alaska presents several features of interest, and in particular it furnishes the best examples yet described of a type of glacier which is not represented in the Old World. The glaciers of Alaska occur almost exclusively on the flanks of the great range of mountains which borders the Pacific coast, and the great expanse of country between this range and the Arctic Ocean is of a very different type; the warm winds from the Pacific are deprived of their moisture by the coast ranges, so that here the precipitation is very great, while to the north the snowfall is small, and Northern Alaska has a very strong resemblance to the great frozen plains, or Tundras, of Siberia.

The coast of Alaska affords numerous examples of tide-water glaciers on a very large scale, but in their general features they scarcely differ from those of Greenland. Two of the largest and best known are the Muir and Taku glaciers. These and others in the same category give off abundance of icebergs.

The coast ranges rise to a great height, culminating in Mt. St. Elias, 18,000 feet, and Mt. Logan, 19,500 feet, the highest peak in North America. Besides the tide-water glaciers already mentioned, they give rise to hundreds, or perhaps thousands, of smaller alpine glaciers which do not reach the sea.

Piedmont Glaciers.—However, the most interesting and remarkable feature of the glacial geology of Alaska is afforded by the class of glaciers to which the name of ' piedmont ' is applied. The upper parts of these piedmont glaciers consist of great ice-streams of the ordinary alpine type. By the confluence of several of these streams a vast mass of ice is formed, in which movement is imperceptible : in fact, the ice is usually spoken of as stagnant. If we compare ordinary alpine glaciers to rivers, by the same analogy piedmont glaciers must be considered as lakes of ice. However, this analogy must not be pushed too far.

The Malaspina Glacier.—The best-known example of a piedmont glacier is the Malaspina,[1] on the western side of Yakutat Bay. It presents to the coast a front of some seventy miles in breadth, and its greatest extension inland is about twenty-five miles : the total area is some 1,500 square miles. It consists of three principal lobes, each of which is the expansion of one or more large alpine glaciers, flowing down from the St. Elias range. The most eastern lobe is fed by the Seward glacier, the middle one by the Agassiz glacier, and the western lobe chiefly by the Tyndall and Guyot glaciers. The Seward lobe ends in a low frontal slope before it reaches the sea, except in one place where it forms the Sitkagi Bluffs on the coast; the Agassiz lobe is fringed by a very extensive series of moraines, as described farther on, while the Guyot lobe reaches the sea and forms bold ice-cliffs. The piedmont glacier proper, as distinguished from the alpine ice-streams which supply it, is a vast, nearly horizontal, plateau of ice, at a general elevation of

[1] Russell, *Glaciers of North America*, p. 109.

about 1,500 feet above sea-level. In its central parts the surface is almost entirely free from moraine, but much crevassed. However, there is one large stream of moraine material, taking its rise in the Samovar Hills between the Seward and Agassiz glaciers, and crossing the whole length of the piedmont ice. These surface moraines present some interesting features; small stones and pebbles sink into the ice, as in Greenland, but the larger masses protect the ice below from melting, so that they eventually come to stand up above the general surface on pillars of ice, forming glacier tables. The stone eventually slips off the pillar, usually towards the south, owing to more rapid melting on that side. A somewhat similar effect arises from the occurrence of long trains of debris running in a longitudinal direction, which eventually rest on elevated ridges of ice; these ridges are thickly covered with moraine, and are described as resembling railway embankments. As the surrounding ice melts the slopes become steeper, and the moraine slips off on each side, forming a double line, which may later on give rise to two parallel ridges. Sometimes more or less circular patches of sand and gravel give rise to cones of ice by a similar process.

On the southern border of the Agassiz lobe are some very extensive moraines, and outside of this is a forest-belt some four or five miles wide. The forest, which is evidently of great age, is growing on moraine, and this moraine in its turn rests on a mass of ice, which is in places at least 1,000 feet thick; hence it is evident that the ice in this part can possess no appreciable movement. Beyond the margin of this forest-belt, and outside the limit of the buried ice, is also a region of dense forest, growing on moraines, which form ridges and hillocks, with many lake-basins. On the south-eastern side, towards Yakutat Bay, there is no forest on the ice, but moraines are very abundant, and here also there are many lake-basins in the ice; these are usually more or less circular, with very steep walls of ice, undercut at the bottom, so that the whole possesses a sort of hour-glass form. The undercutting is doubtless due to more rapid melting of the ice below water-level. Some of these lakes are as much as 200 yards in diameter, but most are only about 30 yards. Their origin is rather uncertain, but some at any rate seem to be formed by the widening of crevasses.

The drainage of the Malaspina glacier is essentially en-glacial or sub-glacial, and surface streams are rare. The Yahtse river, the largest stream of the glacier, rises in the Chaix Hills, and flows through a tunnel in the ice some six or eight miles long; it issues as a stream 100 feet broad and 20 feet deep, and forms an alluvial fan covering many hundreds of acres. The Kame stream, on the east, is peculiar in that it flows for half a mile in an open channel in the ice nearly 100 feet deep. The water of these and other streams is very turbid, and they form great deposits of fluvio-glacial material in front of the ice; it is clear that a large amount of solid matter is brought down in suspension by these streams, and there must be great deposits of sand and gravel in the interglacial portions of their courses.

It appears, therefore, that the principal characteristic of the Malaspina glacier is the stagnant condition of a great portion of it, as evidenced by the growth of an ancient forest on the surface of the ice. The natural inference is that in this case the supply of ice is just balanced by the loss from melting, so that the two factors are more or less in a condition of equilibrium. It appears, however, that in the past precipitation must have been in excess to allow of the accumulation of the enormous mass of ice which now exists. Hence it is probable that a change of climate has occurred in this region.

Transport by Glaciers.—The foregoing detailed consideration of the glaciers of several widely-separated regions shows that all display one common feature, viz. the transport of large quantities of rock-material. Where the ice-streams are surrounded by rock in situ at a higher level, much of this material is visible on the surface, having fallen from the surrounding heights, and in this case it is difficult or impossible to say how much of the material in the lower layers of the ice has a similar origin and how much is derived from the floor over which the ice moves. But in the case of continental ice-sheets—as, for example, in Greenland—surface material is absent in the central parts, since there is no rock at higher levels from which it could be derived. But when the lower layers of such ice can be examined, as for instance at the ends of the glacier-tongues, they are found to be full of moraine material; still more significant is the fact that when the ice is forced against or over any obstruction, moraines are brought to the surface: this is well shown in the case of Jensen's Nunataks (see p. 92). In this case it is impossible to resist the conclusion that this material is torn from the rocky floor by the action of the ice itself, and carried up the flanks of the buried peaks and ridges which constitute these nunataks. It has been observed that the fronts of the Greenland glaciers always show a lower dark dirt-stained portion, and an upper layer of clear ice, which often overhangs. In many cases, both in Greenland and Spitsbergen, the amount of moraine material increases downwards to such an extent that the glacier shades off gradually into its floor with no clear line of division, and in point of fact the supposed ground-moraine is in reality the lowest layers of the ice, which are very heavily charged with *dirt*, to use the favourite American expression.

The observations of Garwood and Gregory [1] on the mechanics of glacier-movement in Spitsbergen are of great importance. They found

[1] *Q.J.G.S.*, vol. liv., 1898, p. 200.

the phenomena most clearly displayed in the case of glaciers with the Chinese wall type of front; the ice-stream advances by an ' over-rolling " movement; masses of ice falling from the projecting upper layers carry debris with them, and the glacier as a whole advances over the talus bank thus formed, producing a series of thrust-planes in an upward direction. By this means material can be raised to a higher level, and in one case where a glacier was advancing over a recently raised beach, material from this could be traced to a height of some hundreds of feet. This observation is significant in respect to certain features in the glaciation of Britain. One of the effects of this kind of movement is to produce distinct lamination of the ice, consisting in an inter-stratification of layers of dirt and ice of varying thickness; these laminæ often show more or less false bedding, and this is believed to be due to shearing rather than to flow. The dirt-bands often show very marked contortion and folding, and indeed most rock-structures may be seen reproduced in laminated ice.

Transport by Glacier Streams.—Besides this transport of material by the ice itself, much solid material is undoubtedly carried along by en-glacial and sub-glacial streams. Some of this debris is doubtless deposited in the channels of the streams, both in and under the ice. The rest is carried by the streams to the ice-front and there deposited as ridges and cones of sand and gravel. It has already been noticed that many of the streams issuing from the Malaspina glacier form great alluvial deposits and deltas by this means, and there can be no doubt that in many cases this is a very important means of glacial transport. Up to the present the large part played by these fluvio-glacial accumulations has perhaps scarcely been properly appreciated. On the recession and disappearance of the ice they leave those characteristic deposits which are known as kames, åsar and eskers respectively.

Advance and Retreat of Glaciers.—Observations extending over a long series of years, in the Alps and elsewhere, have shown that the volume and area of glaciers are never constant for any length of time. Sometimes the fronts are advancing and sometimes retreating, and in the Alps at any rate these variations appear to show a distinct periodicity with a cycle of some thirty-five or forty years. According to Reid,[1] the sequence of events in such a cycle is as follows: the minimum of advance is followed by an increase of velocity, with a rapid pushing forward of the front; then ensues a diminution of velocity with the maximum of advance, followed by a much slower retreat. The advance usually occupies only about one-third of the time of the retreat. This period agrees very well with the climatic cycle of thirty-five years, which has been established from the meteorological records of the last two

[1] *Jour. Geol.*, vol. iii., 1893, p. 278.

R. H. Rastall, photo.

(I) GLACIATED ROCK-SURFACE OVERLAIN BY DRIFT. BORROWDALE, CUMBERLAND.

R. H. Rastall, photo.

(II) GLACIATED ROCK-BARRIER OF LOCH CORUISK, ISLE OF SKYE, WITH *ROCHES MOUTONNÉES.*

centuries. Two theories have been put forward to explain the mechanism of this advance and retreat. Richter's ' Theory of Intermittent Flow ' supposes that increased snowfall causes greater pressure and drives the ice forward until the drain by the more rapid flow exhausts the accumulation of névé and ice. Forel, on the other hand, believes that the flow is continuous. According to him, when the snowfall increases the upper part of the glacier increases in velocity. This results in a thickening of the ice downwards. When this increase of thickness reaches the lower end advance begins. As the snowfall diminishes the glacier also decreases in thickness and velocity, till the rate of melting exceeds the rate of flow, when it again begins to retreat.

Vanished Glaciations of the Past.—Of much more importance, however, are the variations on a large scale which have undoubtedly taken place in the past. There is abundance of evidence to show that large areas which now enjoy a temperate climate were once buried under great masses of ice and snow, which probably bore a strong resemblance to the present continental ice-sheet of Greenland and the polar ice-cap of the Antarctic continent. It is clear that near the end of Tertiary time glacial conditions were very widespread in the north-west and north of Europe, and in North-east America. At the same time the glaciers of the Alps had an enormously greater extension than now, and many of the lesser ranges of Central and Southern Europe also possessed independent systems of glaciation. This is not the place to discuss the causes of the Glacial period, which is still one of the most vexed questions in geology, but since it undoubtedly had a most important influence in creating or modifying the present topography of many of the best-known regions of the earth, it is essential here to consider somewhat in detail some of the effects which it produced.

Evidences of Past Glaciation.—We have already seen that living glaciers give rise to characteristic accumulations at the ice-front and along the sides of the containing valleys, in the form of moraines and accumulations of debris of various kinds. Besides this, however, glaciers leave their mark on the rocks over which they pass, in the form of rounded, grooved, striated and polished surfaces. This can be seen in any region of retreating glaciers, and affords the surest indication of the former presence of glaciers in regions from which they have vanished. The surfaces over which ice has passed are rounded and polished in a manner very different from any possible effects which could be produced by water-erosion, resulting in a peculiar and easily recognisable type of topography (cp. Plate XV (ii) and Plate XVI). A specially characteristic feature is the occurrence of what are known as ' roches moutonnées,' i.e. rock masses which have been rounded off, and present a convex surface on the side from which the ice came, while the lee-side is usually quite rough and angular.

Roches moutonnées are very well seen in many of the upland districts of Britain, such as North Wales, the Lake District, and Scotland, and they are associated with deposits which show all the characteristics of the moraines of modern glaciers. It may be said that the secondary effects of glaciation are more clearly seen in regions from which the ice has departed than where it is still present to hide its own work, and the study of the glacial phenomena of Britain and North America has done much to elucidate the details of modern glacial action.

Erosion by Ice.—The question of the efficiency of ice as an agent of denudation has given rise to much discussion, and even now opinions differ very widely. Some authorities deny that its effects can ever be anything more than superficial, while others ascribe to it great importance in land sculpture. The abundance of lakes in glaciated regions led some writers, especially Ramsay, to suppose that they all lay in basins which had been scooped out by the erosive power of the ice. At a later date arose a school of geologists who were inclined to deny the possibility of the erosion of a rock-basin by ice, or indeed by any other means. It was asserted that such a thing as a rock-basin in this sense did not exist; that in all cases there must be a buried outlet, or that the water was simply held up by a dam of moraine and drift; and as a result of much detailed work it has been shown that in a great number of cases this is the true explanation. But there remain a number of instances in which it is evident that the lake is everywhere surrounded by rock in situ, with no possibility of a buried channel. Such is Thirlmere, and on a smaller scale Watendlath Tarn in the Lake District,[1] and Cwellyn and Glaslyn in the Snowdon area.[2] But perhaps the most convincing example of ice-erosion occurs in Skye, which has been studied in much detail by Harker.[3] The following is a summary of his conclusions :—

Ice-erosion in the Cuillin Hills, Skye.—At the period of maximum glaciation the island of Skye supported a small local ice-cap, which was able to repel the invasion of the Scottish ice-sheet. This ice-cap had its centre in the Cuillins and Red Hills, which formed a gathering ground of some forty square miles in extent: the mountains were completely buried in ice, which was some 3,000 feet thick. The carving out of the Cuillins in its broad features was due to preglacial water-erosion, but the details of the relief are clearly due to ice, and this results in a peculiar type of topography. The whole surface of the mountains exhibits strongly marked rounding, striation and polishing, except on the extreme peaks, where it has been obliterated by frost weathering. Here

[1] Marr, *Pres. Add. Geol. Soc.*, 1906, p. cxxv.
[2] Jehu, *Trans. Roy. Soc. Edin.*, xl., 1901–2, p. 419.
[3] *Trans. Roy. Soc. Edin.*, xl., part ii., p. 221.

the chemical factor in weathering is in abeyance, and only the mechanical agencies are of importance. Consequently, the conspicuous features are carved out almost irrespective of the lithological character or physical structure of the rocks, and the Law of Structures does not apply. Rocks of very varying degrees of hardness are ground down to one uniform plane or curved surface.

The tendency of ice-erosion is to produce a simplification of valleys in ground-plan and cross-section ; spurs are destroyed, curved reaches straightened, and subsidiary ridges planed away ; the floor of the valley is widened, and the walls become straighter and steeper. But with regard to the longitudinal section, the above considerations do not wholly apply.

In many cases the thalweg of the valley is not a uniform concave curve, as in mature rivers; but ice-erosion tends, within certain limits, to accentuate inequalities, instead of levelling them up. So long as the upper surface of the ice has a downward inclination, the amount of erosion varies directly as the thickness of the ice, since it depends on the pressure acting on the floor. If this floor is irregular the ice will be thicker over any hollows, and will tend to deepen them. This process has produced some true rock-basins, which contain lakes of considerable size. The best example is Loch Coruisk, which is about 1½ miles long and one-third of a mile wide. Soundings show that it consists of two deep hollows separated by a ridge, which bears several small islands. The surface of the water is about 25 feet above sea-level, and the depth of the lower basin is 125 feet, so that it descends 100 feet below sea-level ; the upper basin has a maximum depth of about 90 feet. The whole is visibly surrounded by rock, except for a gravel-flat at the head, and the bottom consists of bare rock. In the Camasunary valley are two smaller lakes of a similar kind.

The evidence of erosion afforded by the distribution of boulders in the Sligachan valley is very striking. The eastern side of this valley in its upper part consists of granite, the western of gabbro ; the lower part of the valley passes over basalt. In the upper part nearly all the boulders on the right side of the central line of the ice-stream, which practically coincides with the junction of the two rock types, are of granite, while on the left an equally large proportion are of gabbro (see Fig. 42). So soon, however, as we cross the line dividing these rocks from the basalt, boulders of the latter rock make their appearance in gradually increasing numbers, till in a short distance they form the great majority. It is clear that here the boulders are fragments of the country rock, which have been torn from their bed and carried along by the ice-stream. The transport is therefore solely in a downward direction, and boulders of basalt are never found at a higher level than the same rock in place.

Glacier Lakes.—Lakes of various kinds are a very common feature of glaciation, and may be formed in various ways. The origin and character of the lakes which are so abundant in regions of vanished glaciers is treated elsewhere, and it is only necessary to consider here lakes associated with contemporaneous glacial conditions.

During seasons of rapid melting pools of water frequently collect in hollows on the surface of the ice; but these are usually short-lived and of small importance, since they are commonly drained off by crevasses.

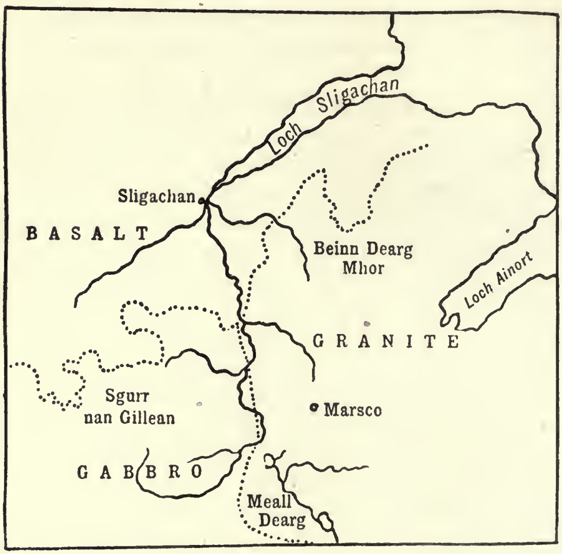


FIG. 42.—MAP OF THE SLIGACHAN VALLEY.

(After Harker, 'Tertiary Igneous Rocks of Skye,' *Mem. Geol. Survey,* 1904.) Scale, ½ inch to 1 mile (slightly diagrammatic). The dotted lines show the boundaries of the different rocks in place.

Reference has already been made to the peculiar hour-glass-shaped lakes of the Malaspina glacier, which appear to be somewhat of this nature. When two ice-streams coalesce, a lake is frequently formed in the angle between them, lying partly in the ice and partly on rock. A well-known example is the Lac de Tacul, lying between the Glacier de Géant and the Glacier de Leschaux in the Mont Blanc region. The waters of such lakes are usually of a peculiar greenish-blue colour.

The Danish explorers in Greenland [1] have described curious small circular lakes in the hollows on the lee-sides of nunataks, often surrounded

[1] *Meddelelser om Grönland,* vol. i., 1879, Plate V, *C′*.

PLATE XVII

J. J. Lister, photo.

(I) ICE CLIFFS OF THE MÄRJELEN SEE, BERNESE OBERLAND.

W. Lamond Howie, photo.

(II) THE PARALLEL ROADS OF GLENROY.

by high cliff-like walls of ice. One such on the west side of Jensen's Nunataks has a diameter of over 250 yards.

A peculiar type of glacier lake has been described in Alaska. Some of the glaciers of this region appeared to be shrinking at the head downwards, probably owing to a failure in the supply of snow; and when this is the case, lakes are sometimes found in the hollow above the glacier from which the ice has retreated.

A glacier coming down a tributary valley may hold up the drainage of a main valley and form a lake. This is not common except in a temporary way, since such ice-barriers are soon destroyed. A very remarkable case is that of the Vernagt glacier in the Tirol, which periodically extends itself enormously at a very rapid rate; it comes down a steep side valley, the movement being partly ordinary glacial flow and partly an ice-fall, and sometimes forms a lake nearly a mile long and 300 feet deep. Similar phenomena are known in the Caucasus and Himalayas. Such lakes are short-lived, since the barrier either bursts suddenly and causes disastrous floods, or is slowly washed away by melting and current action.

A more important case is where the drainage of a tributary stream is obstructed by ice in the main valley. Perhaps the best example of this is the oft-described Märjelen See at the elbow of the great Aletsch glacier (Plate XVII (i)). This is peculiar among glacier lakes in that it possesses a maximum level beyond which it can never rise, since at the head of its valley is a low col, leading over into the valley of the Viesch glacier. This may give rise to a definite beach at the level of the col, and this observation has an important bearing on the origin of certain phenomena in Britain, hereafter to be described.

Many of the ice-streams descending from the inland ice of Greenland block up tributary valleys and produce lakes of this kind on a very large scale. The lake of Tasersuak, on the west coast of Greenland, is some 12 miles long by about 2½ miles broad. It is in reality a fjord which is dammed by the great Frederikshaab glacier; on the other side of the same glacier is another corresponding dammed valley, and this phenomenon is not uncommon in that region. Lakes of this type are of particular interest to us, because it has recently been shown that some peculiar topographical features in the north of England and Scotland are explicable on these lines.

The Parallel Roads of Glenroy.—The celebrated Parallel Roads of Glenroy, Argyllshire (Plate XVII (ii)), are narrow terraces or beaches 40 to 50 feet in width, running horizontally along the mountain slopes; they consist chiefly of angular detritus of local rocks. They occur at heights of 1,153, 1,077, and 862 feet respectively, which correspond exactly with the levels of three cols—one at the head of the main glen, one in a tributary glen, Glas Dhoire, and one at the head of Glen

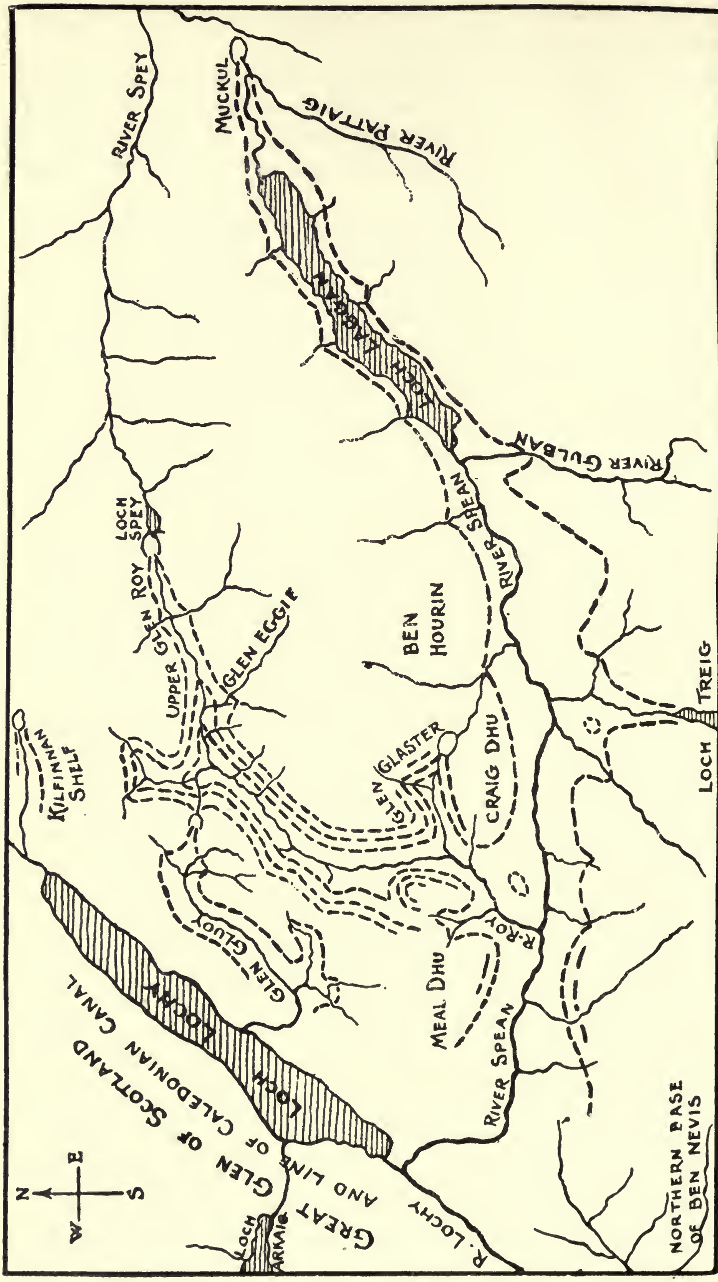


FIG. 43.—DIAGRAMMATIC MAP OF THE PARALLEL ROADS OF GLENROY. (After Lyell.)

Laggan, into which the lowest 'road' passes.[1] At the time of greatest advance of the ice, the drainage of the valley was blocked till it overflowed into the Spey basin over the high col at the head of Glenroy. As the ice-front withdrew southwards the lower cols were successively uncovered, and the water-level remained sufficiently long at these levels to form distinct beaches, the present 'roads.' They were formerly held to be ancient sea-beaches formed during a period of submergence, but this view is now universally abandoned (see Fig. 43).

Glacier Lakes in Northern England.—In the highly glaciated area of northern England evidence has been brought forward by Kendall, Dwerryhouse and others, showing the existence of a highly developed system of glacial lakes, due to the damming of river valleys by great glaciers, and in particular by the North Sea glacier, and those of the Eden valley and Teesdale. It is here necessary to anticipate part of our description of the glaciation of Britain, which will be found in the stratigraphical part of this volume. However, without entering into detail, we may say that local glaciers passed from the drainage basin of the Irish Sea over the Pennine chain into the valleys of the Tyne, Wear, Tees and other eastward-flowing rivers ; also, according to the commonly accepted view, the North Sea was filled by a great mass of ice, derived from various sources, which encroached on the north-east coast, blocked up the mouths of the valleys, and was forced inland, often for a considerable distance, by the pressure behind.

A great mass of ice from the Lake District and the Solway basin, carrying many characteristic boulders, was forced up over the Stainmoor Pass and blocked up the upper part of Teesdale,[2] and formed large marginal lakes of the Märjelen type, which have left abundant traces behind them. Local glaciers also flowed down the eastern slope of the Cross Fell range, by the valleys of the Tees and Wear. One of these glaciers blocked up the valley of the Maize Beck and formed a large lake, which probably drained over High Cup Nick on to the surface of the Edenside ice, which here stood at a lower level. The Solway ice also flowed down Tynedale and held up many lakes in the valleys of the Allen, Devil's Water and Derwent. All these lakes formed overflow channels of a peculiar character, which will be described in detail later on.

Turning now to the Cleveland district[3] in N.E. Yorkshire, we find that the great North Sea ice-mass was forced in upon the coast, and penetrated inland for a distance of several miles ; the Cleveland Hills, though rising to a height of over 1,400 feet, possessed no local glaciers,

[1] Geikie and Lamond, *Brit. Ass. Geol. Photographs.* Description of No. 1815, 2nd Series.

[2] Dwerryhouse, *Q.J.G.S.*, 1902, p. 572.

[3] Kendall, *Q.J.G.S.*, 1902, p. 471.

but along their northern slopes the ice rose to a height of some 1,000 feet above sea-level. This ice over-rode the watershed to the north of the Esk valley at a height of about 850 feet, and blocked up this valley at several points, corresponding to comparatively low cols in the northern watershed. At the period of maximum extension the lower part of the valley was completely blocked and all drainage to the sea was prevented. The water of the river system, together with great volumes from the melting margin of the ice, accumulated till it formed a great lake, occupying the whole of Eskdale and its tributary valleys above Grosmont to a height of about 725 feet. This, which is called

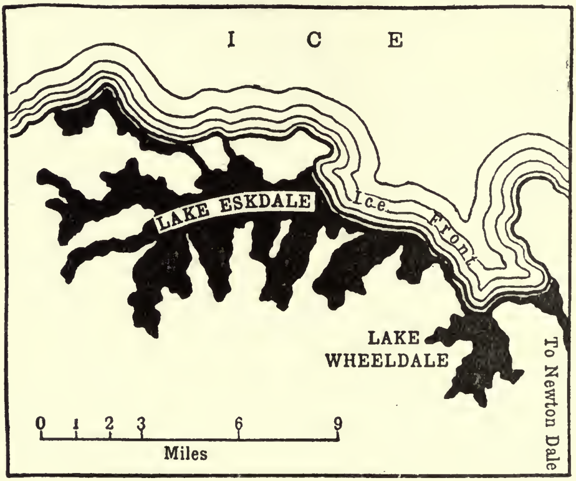


Fig. 44.—Map of Lake Eskdale at its Maximum Extent. (After Kendall.)

by Kendall 'Lake Eskdale,' was about eleven miles long, and at least 400 feet deep (see Fig. 44).

Since all direct outflow to the sea was prevented, the water accumulated till it found an outlet elsewhere. In this case the outlet was found over a sharp spur separating Eskdale proper from the valley of a southern tributary, the Mirk Esk, and over this spur the water flowed in enormous volumes. This rapid flow produced great erosion, and soon cut a conspicuous notch in the spur. As the ice retreated or melted away this process was repeated at a lower level, and the spur in question shows a series of parallel notches one below the other, corresponding to pauses in the retreat of the ice. These notches are the 'overflow channels' of Kendall, and they show a very characteristic form; they always possess a flat floor and very steep sides, giving a conspicuous U-shaped section. They occur in large numbers all over the glaciated areas of the north of England, and most of them are now quite streamless.

The water from Lake Eskdale eventually found its way over a col at the head of a valley flowing down towards Pickering, which is greatly deepened and enlarged, forming the magnificent gorge of Newton Dale, through which the railway from Pickering to Whitby now runs. The

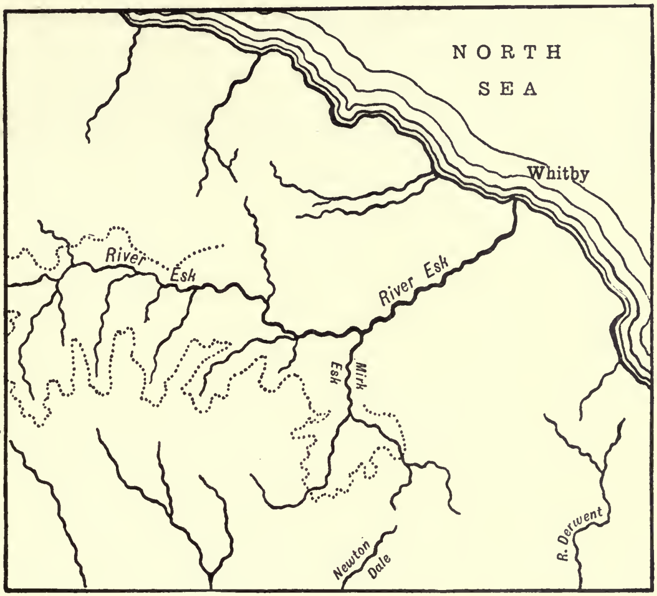


Fig. 45.—The Present Drainage System of Eskdale.

The dotted line indicates approximately the maximum extension of the glacial lakes. Scale, 4 miles to 1 inch.

highest point of the rocky floor of this valley is at 525 feet above sea-level, so that when the overflow stream had cut down to this point the lake had evidently found an outlet elsewhere, presumably owing to the retreat of the ice in the lower part of Eskdale, which had opened a direct channel to the sea, past Whitby (Fig. 45).

The encroachment of the North Sea ice also brought about remarkable changes in the course of the Yorkshire Derwent. In preglacial times the wide Vale of Pickering, extending westwards from the coast south of Scarborough, was drained by a stream which probably flowed into the sea near Filey. The North Sea ice extended some seven or eight miles inland and converted this region into a lake. The water accumulated until it reached the top of a col south of Malton at an elevation of some 250 feet; it then proceeded to carve out the great gorge in which Kirkham Abbey is situated, and which still forms the channel of the Derwent. The original valley is blocked at Filey by a barrier of drift about 150 feet high, and the main stream, which collects the drainages of the moorlands to the north, now flows almost due west from Ganton towards Malton, cuts through the southern escarpment, and flows into the Ouse drainage basin. Thus as a direct consequence of glaciation we have the remarkable result that streams which rise not more than two or three miles from the sea, near Robin Hood's Bay and Ravenscar, finally flow into the sea by the Humber, after a course of nearly a hundred miles. There is no stream of any consequence flowing into the sea anywhere on the long stretch of coast between Whitby and Spurn Point.

CHAPTER VII

MARINE DENUDATION

In the introductory chapter it was pointed out that the waters of the ocean are in a constant state of movement, and that the movements are due to various causes. The most important of these are the rotation of the earth, variations of temperature and pressure, and different degrees of salinity in the water itself. All these factors interact in a complex manner, into which we cannot here enter in detail. It must suffice to say that the final resultants of all these forces manifest themselves under three chief forms, which can for our present purpose be summarised as waves, currents and tides. The origin of tides is well known to be a cosmical one, due to the rotation of the earth and the differential attractions of the sun and moon ; waves are largely, if not entirely, due to wind : earthquake waves, though less frequent, produce enormous changes when they do occur ; while the origin of currents is usually more complex, since they are due in part to tides, in part to winds, and in part to variations of temperature and salinity. All these causes together result in a continual and ever-varying circulation of the surface waters of the globe, in their efforts to attain to an equilibrium which is never reached.

It is obvious that this great moving mass of water must possess dynamical energy which is capable of doing work, and part of this work takes the form of destructive and constructive processes along the zone of contact between the land and the sea, and on the bed of the sea itself. It has been pointed out by Gilbert that the forms of land are due chiefly to denudation and the forms of the sea-bottom to deposition, while the forms of shore-lines are a combination of the two, but possessing special characters of their own, since they are very largely due to the action of water-waves, complicated on ocean shores by the tides.

Just as in the case of the destruction of the land, marine denudation can be considered under the three headings of weathering, transport and corrasion. However, the relations are not so clear, because we can rarely find an area of denudation free from deposition, since the sea is the final resting-place of all the material derived from the land.

As regards the agents of denudation, it is necessary to distinguish to a certain extent between denudation of shore-lines, in which waves are the chief agent of erosion, and transport is performed by waves and currents jointly, and subaqueous denudation, in which both erosion and transport are due to currents.

Wave-action.—Without entering into a discussion of the mechanics of wave-motion, we may say that the direct sphere of action of waves is limited below by the level of the trough of the wave and above by the level of the crest. Owing to the dash of water thrown up by the wave, the effect really extends higher than this in a diminished degree. Owing to undermining and so on, the indirect effect of waves may extend upwards to an unlimited height.

The impact of waves of pure water, free from sediment, upon hard homogeneous rock would probably produce little or no effect, although if the rock was soft or well-jointed its effect might be great. However, just as in the case of the running water of the land, the tools of wave erosion are the rock-fragments which are transported by the waves, and which at the same time themselves undergo comminution.

The actual mechanical power of sea-waves is enormous; the average pressure of the Atlantic waves on the western coasts of Britain is estimated at 600 lb. to the square foot in summer and 2,000 lb. in winter, while in a storm the wave-pressure of the North Sea at Dunbar was found to be 3½ tons per square foot. Besides the direct pressure or force of the blow delivered, waves also act indirectly in other ways. When a wave surges up the face of a cliff and forces its way into the cavities and along the joint-planes of the rock, the air within these cavities is suddenly and forcibly compressed, so that the effect of the blow is felt far beyond the region actually reached by the water. For this reason the forms assumed by cliffs of hard rock under the influence of wave-action depend primarily on the nature and direction of the joints. In soft or unjointed homogeneous rocks the forms assumed are less definite, depending on the character of the rock.

Forms of Shore-lines.—From these considerations it is evident that the form of a shore-line is controlled very largely by the structure of the rocks of which it is composed; that is to say, the Law of Structures holds good here also, with limitations. But this is not the sole factor concerned. It is well known that while the majority of coasts are undergoing destruction, in some cases the opposite process is taking place, and the land is actually gaining on the sea. This is always due to certain special conditions, which will be considered in due course. It may be pointed out here, however, that this state of affairs appears to be usually a temporary one, and apart from actual elevation, the ultimate fate of land masses is destruction.

The destructive action of the sea is seen to its fullest extent along

R. H. Rastall, photo

(I) CLIFF AND BEACH AT HUNSTANTON, NORFOLK. LOWER GREENSAND, HUNSTANTON RED ROCK AND CHALK.

Photo by H.M. Geological Survey.

(II) CLIFFS OF CAMBRIAN DOLOMITE, WITH CAVE DUE TO MARINE EROSION. SMOO CAVE, DURNESS, SUTHERLAND

those coast-lines where the subaqueous slope is abrupt, with deep water close to land, since here the waves can exert their fullest power: where the slope is very gradual, the waves break far from land and have lost much of their energy through friction before they reach the shore. In such areas deposition often occurs off shore to such an extent as to build up bars, sandbanks, shoals and other accumulations either just above or just below the surface.

In the study of the topographic forms of existing shore-lines, a special difficulty arises from the fact that it is usually impossible to decide whether the features seen are actually due to wave and current denudation at and near sea-level, or whether they are due to the complete or partial submergence of structures formed as the result of denudation of a land-surface. In many cases it is quite certain that the peculiar features of certain shore-lines are due to this latter cause. As examples,

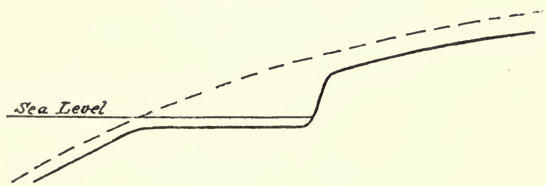


Fig. 46.

The dotted line represents the original form of the uplifted land; the continuous line shows the wave-platform and cliff after denudation has been proceeding for some time.

special mention may be made of the fjords of Norway and the sea-lochs of the western Highlands of Scotland, which are generally considered to be due to the 'drowning' of valleys formed by subaerial denudation when the land stood higher relatively to the sea than it now does.

Cliffs.—It is only under exceptional circumstances that the land-surface passes down below sea-level in an unbroken regular slope. The coast-line is nearly always marked by a more or less abrupt slope, which is commonly spoken of as a cliff (Fig. 46). The formation of a cliff (Plate XVIII) is not a simple process, but is the resultant of several causes. In the first place, we have the action of the waves and currents acting at the base only, thus tending to undermine the land; and, second, there are the ordinary subaerial agents of denudation acting on all points of the cliff, and tending to wear away the upper parts faster than the lower, and thus reducing the steepness of the slope. The ultimate form of the cliff thus depends on three principal factors: the structure and nature of the rock, the rate of marine denudation, and the rate of subaerial denudation. Since all these factors may vary indefinitely, a great diversity of forms may be produced. Some of the conditions which specially favour the formation of steep cliffs are,—rapid marine erosion acting on hard rocks which are but little affected by the weather: in this case the resulting forms depend primarily on the

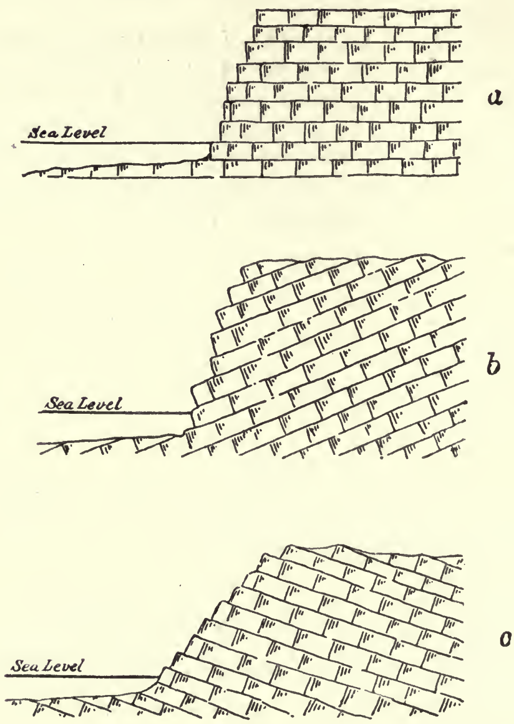


FIG. 47.—BEDDING PLANES.

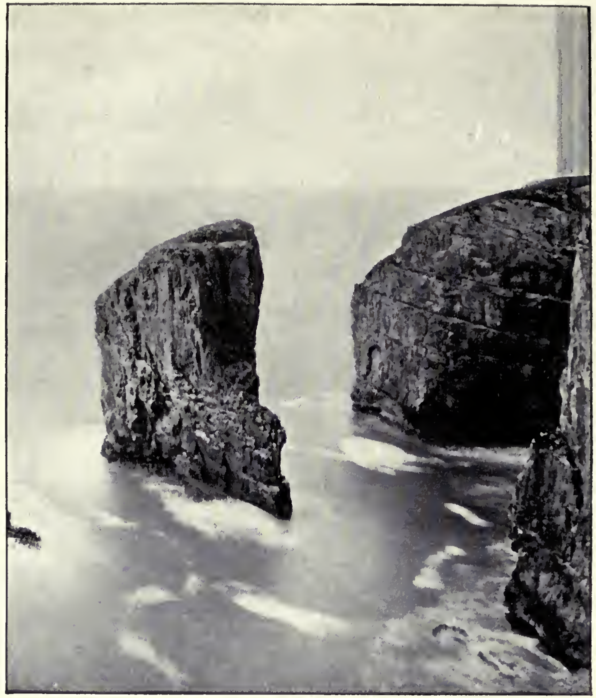
a, Horizontal; *b*, Dipping towards the sea; *c*, Dipping away from the sea.

disposition of the joints, as is shown in Fig. 47; second, steep or even overhanging cliffs are often produced when soft rocks are overlain by a harder layer, as is well seen in many parts of the north-east coast of Yorkshire, where cliffs of soft shale are capped by thick beds of hard and well-jointed sandstone. Even such an apparently soft rock as chalk often forms steep cliffs, where it is rapidly undercut at the base by wave-action; good examples of such cliffs are seen at Dover, Beachy Head and Flamborough Head. A special feature of chalk cliffs is

PLATE XIX

Photo by H.M. Geological Survey.

(I) NATURAL ARCH IN CARBONIFEROUS LIMESTONE. MANORBIER, PEMBROKE.



(II) STACKS ON THE COAST OF PEMBROKESHIRE.

the readiness with which they form caves and isolated pinnacles, such as the Needles at the western extremity of the Isle of Wight, and the King and Queen rocks at Flamborough Head. In this case wave-action is possibly assisted to some extent by solution.

However, the formation of isolated pinnacles of rock is not by any means confined to chalk. Innumerable examples exist around the British and other coasts, in rocks of every kind. A well-known example on a very large scale is the Old Man of Hoy, in the Orkneys, so graphically described by Sir Archibald Geikie.[1] The *stacks* on the coast of Pembroke (Plate XIX (ii)), and those near Duncansby Head in Caithness, may also be mentioned.

When marine erosion acts on unjointed rocks somewhat different effects are produced, and these are specially notable in regions where there is little or no tide. A good example has been described by Günther[2] in the island of Capri, which consists for the greater part of fairly homogeneous limestones. Here the most conspicuous feature is the formation of a deep groove at mean tide-level, and the cliffs above it frequently overhang. In Capri similar grooves occur at different heights above present sea-level, indicating recent uplift and tilting of the land, since the height of the most conspicuous groove varies from 23 feet at one end of the island to 12 feet at the other. This movement has occurred since the first century A.D. The raised cliffs and terraces of Christmas Island,[3] which are cut out of reef-limestones of various ages, also overhang very markedly as a result of wave-action. In fact, undercutting of this kind is one of the most conspicuous features to be seen in the raised reefs of the Pacific.

Comminution of Material. — We must next consider the effect of corrasion by wave and current action on the material itself. The primary source of beach-material is to be sought in the fragments which are detached from the cliffs and shore-platform by the force of the waves, and its character naturally varies according to the kind of rock acted on. These fragments are constantly rolled hither and thither, so that they gradually become less and less in size and much rounded and smoothed. This smoothness is highly characteristic of beach-material, and it is also clearly to be seen in the rock-surfaces still in situ, over which wave-action has full play, so that rocks on the shore are for the most part exceedingly slippery, and this slipperiness is accentuated by the coating of sea-weeds which so often covers them. The larger blocks and shingle of the beach, by a constant movement to and fro, become smaller and smaller, so that they are eventually

[1] *Geological Sketches at Home and Abroad*, p. 26.

[2] *Geographical Journal*, August 1903, p. 121.

[3] C. W. Andrews, *Monograph of Christmas Island*, p. 6, &c.; *Geographical Journal*, vol. xiii., 1899, p. 17.

ground down to sand. The form of sand-grains depends on the conditions under which they are formed, and the sand of sea-beaches is as a rule moderately rounded, less so than in the case of desert sands. Occasionally, however, where sand has remained for a long time in an eddy, the grains become very rounded. The mineral constitution of sands is fully treated in a later chapter.

Wave-cut Terraces.—When a shore-line composed of hard rocks is undergoing rapid denudation by wave-action, there often extends from the foot of the cliffs for a considerable distance out to sea a submerged platform of rock having a surface which is approximately the lower limit of wave-action, and from this platform unusually hard masses of rock often project, either above water-level or just below it. These are variously known as reefs, shoals, skerries, scaurs, &c., and their varieties are endless. When these projecting rock masses are of considerable size they are usually dignified by the name of islands.

Such are some of the more characteristic features of rocky coasts where denudation is extensive and deposition of little importance. They are well seen in many regions which are exposed to the action of the waves of the open sea, as, for example, on the western sides of Scotland and Ireland, Brittany, N.W. Spain, Portugal, &c.

Transport of Material.—We have seen in the preceding paragraphs that waves are the principal agent in the denudation and shaping of shore-lines; it remains to consider now the effect of the other forces which play a part in the geological activity of the sea. The effect of the tides chiefly resolves itself into the production of waves and currents, at any rate in shallow water near land; currents act in conjunction with waves as transporting agents, and distribute the loose material, which has been prepared chiefly by wave-action.

It is a special peculiarity of wave-action on a normal gently sloping shore, that for waves of a given magnitude there is a certain critical size of material—shingle or sand as the case may be. All fragments above this critical size tend to be moved towards the land and piled up on its margin, whereas fragments below this limiting size travel away from the land, towards deeper water. This curious phenomenon results from the oscillatory nature of wave-motion, with an alternation of rapid forward motion and somewhat slower backwash. The coarser material is therefore deposited on the shore-line, usually near high-water mark, or a little above it; below this the material gradually becomes finer and finer towards the sea, while the finest of all is carried below the limits of wave and current action and forms the ordinary marine deposits, which will be described in detail in due course.

Beaches and other Accumulations of the Shore-line.—The material which is thus cast upon the margin of the land by wave-action, assisted

Photo by H.M. Geological Survey.

(I) PEBBLE BEACH. SENNAN, CORNWALL.

Photo by H.M. Geological Survey.

(II) CLIFFS DETERMINED BY JOINTING IN GRANITE. LAND'S END, CORNWALL.

by currents, constitutes what is commonly known as the beach (Fig. 48). Beaches consist of rock-fragments, and are popularly spoken of as consisting of sand, shingle, &c., according to the size of the fragments, which varies according to the different conditions. The form and character of the beach as a whole also vary according to the strength of the waves, currents, &c., to which it owes its origin, and the nature of the materials of which it is composed. In a region of hard rocks exposed to strong wave and current action there is often little or no beach, and on coast-lines of strong relief beaches are commonly developed in the indentations only. On the other hand, gently sloping shores of soft rock are often bordered by great accumulations of beach-material. As a rule, beaches show the highest development where the submarine slope is very gentle, but they depend so much on individual conditions that it is difficult to lay down any general laws.

Thus the general effect of wave-action is to pile up the shingle of the beach in a ridge at or near the line where the waves break.

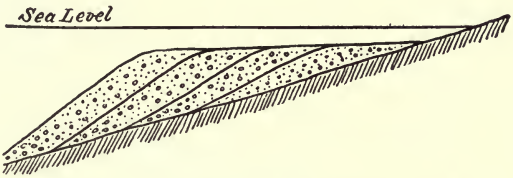


FIG. 48.—FORMATION OF BEACH DEPOSITS.

It appears that the maximum deposition takes place below the line of maximum agitation of the water. On steep shores this is close to the land, often actually at the foot of the cliffs. But on a gently sloping shore the waves often break far out, so that the maximum deposition takes place some distance from land. This may eventually result in the formation of an off-shore barrier, with a lagoon behind it, as is seen on many low coast-lines. Similar barriers are often formed across small bays, but here another factor comes into play also: transport of material along the shore by currents, or by the combined effects of waves and currents, and this must now be considered.

Transport along Shore-lines.—Material may be transported along shore-lines in either of two ways. The most obvious method is by a current running parallel to the coast, and due to tides, winds, or general water circulation. But similar transport can also be effected by wave-action alone; if the prevailing direction of waves due to the wind is more or less oblique to the coast, shingle and sand carried up by the waves will also have a more or less oblique direction. But the back-wash runs down the steepest slope at right angles to the shore-line, so that material thus travels in a kind of zigzag manner, and may be carried along the shore with comparative rapidity. The direction of motion is obviously governed by that of the prevailing wind; this is well seen in the English Channel, where there occurs a very con-

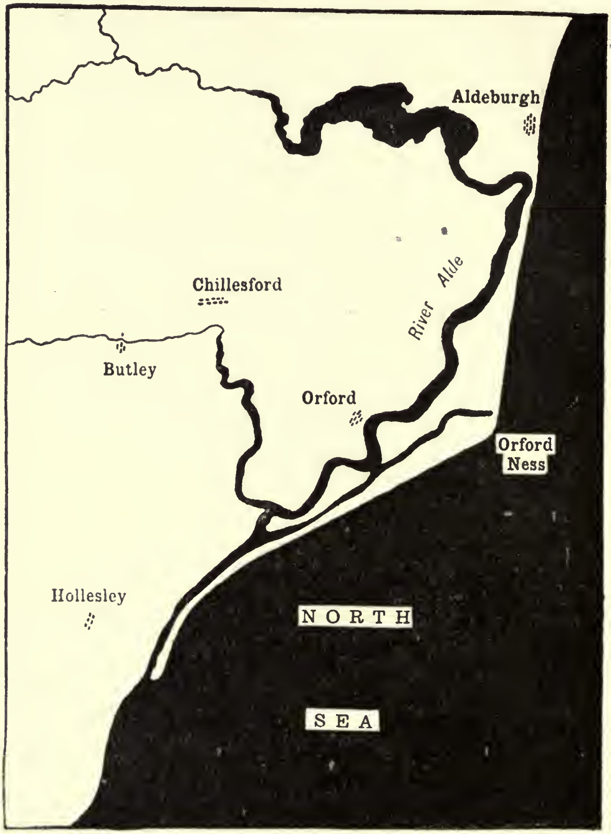


FIG. 49.—THE RIVER ALDE, SUFFOLK.
Scale, 1 inch to 3 miles

spicuous migration of shingle from west to east. This effect is well known at many of the south coast watering-places. In many places elaborate systems of groynes and other constructions have been erected in an attempt to arrest the eastward progress of the shingle.

One of the most important accumulations of shingle in this country is the well-known Chesil Beach,[1] which borders the coast for many miles

[1] Vaughan Cornish, *Geographical Journal*, vol. xi., 1898, p. 628.

west of Portland. Behind the shingle beach is a long narrow lagoon, known as the Fleet. The chief difficulty with regard to the source of the material of this beach lies in the fact that the pebbles are large at the eastern end and smaller towards the west; this is the opposite of what would be expected from a consideration of the general easterly drift in the Channel. It appears, however, that material is really supplied to the beach from both ends, and not from the eastern end only, as formerly supposed, and the material fed in at the western end is mostly fine, the coarse material from the west being stopped by small promontories. The material supplied from the east, on the other hand, is mostly coarse, and at the present time a large proportion of it consists of rubbish tipped from the Portland quarries; at this end there is a strong outward current which carries off much fine material, and so increases the proportion of large fragments.

Other interesting cases of peculiarities of topography due to drift by along-shore currents are to be found on the eastern coast of England, and especially in Norfolk and Suffolk. The prevailing set of the tides and currents in the North Sea is southwards, so that there is a pronounced southerly drift of material along the coast. The effect of this is well seen in the course of the river Alde, which approaches within a mile of the sea at Aldeburgh, and then turns abruptly somewhat to the west of south and flows for ten miles or more parallel to the coast inside a great bank of shingle (see map, Fig. 49). A similar phenomenon is to be seen at the mouth of the Yare and Waveney, near Yarmouth.

Sand Spits.—When an along-shore current of the type above described reaches the mouth of a bay or estuary it passes into deeper water, and is therefore unable to carry its load, owing to the absence of agitation in the deeper layers. The material is consequently dropped, and in course of time will build up a ridge of shingle or sand which may extend completely across the opening. More commonly, however, the scour of the tides and of rivers keeps a channel open, generally at or near the farther side towards which the current is travelling, and the result is a *spit*. The manner of formation of a spit is essentially like that of a railway embankment, in which the material is carried along the top and tipped over the end, thus continually lengthening the embankment. An excellent example of this kind is to be seen in the long spit of sand and shingle which stretches out from Spurn Point partly across the channel of the Humber (Fig. 50), and this shows very well the recurved form which is so characteristic, and is due to the combined action of waves and currents, both inward and outward, but dominantly from the north.

General Forms of Coast-lines.—The most complete and systematic treatment of the topography of shore-lines is due to American geologists, who have studied in much detail the phenomena presented by the coast-lines both of the sea and of large fresh-water lakes. The phenomena presented in the two cases are not quite identical, owing to the absence of tides in the latter. The most complete study of shore-line topography is that of Gulliver,[1] and his most important conclusions may be summarised as follows. Starting from the assumption of a constant state of change in the relative levels of land and sea, the forms of the actual shore-line are shown to depend very largely on the nature and direction of the last movement. Two ideal types are fully described: the first is due to a uniform uplift of the land, and the second to a uniform depression. We may begin with the conception of an uplift of a given land area to a certain height above sea-level. During

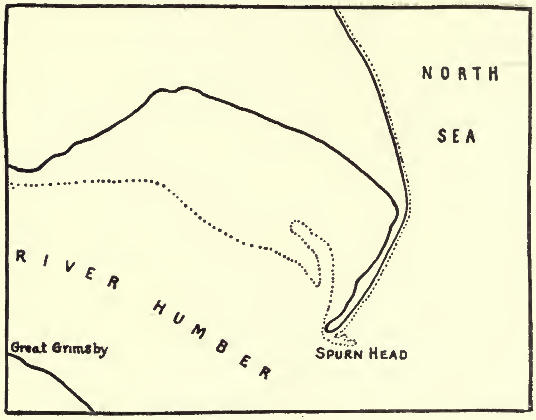


FIG. 50.—SPURN HEAD, AT THE MOUTH OF THE HUMBER.

The dotted line is low-water mark.

the period preceding the uplift, the sea floor off the land will have been smoothed down by the usual processes of deposition, so that the newly exposed land-area will have smooth simple contours, and a coast-line usually in long smooth curves. Behind this smooth coastal belt lies the older land-surface, which is usually of more varied relief and steeper slopes, so that it is easy to trace the old shore-line in its new inland position. The amount of contrast between the new land and the old will, of course, depend on the amount of denudation which the latter has undergone. In some cases, where the old land-surface was in the middle stages of its cycle of denudation, the contrast is very sharp. A coastal plain of this kind is well seen along the Atlantic shores of the United States, especially in North and South Carolina and

[1] *Proc. Amer. Acad. Arts and Sciences,* Boston, vol. xxxiv., 1899, p. 151.

Georgia.[1] Behind it comes a region of moderate relief, which is called by Davis the Piedmont Belt, and still farther inland stretches a range of high mountains. Other examples of similar coastal plains are to be found in the Argentine Republic, east of Buenos Aires, and along the east coast of India, north of Madras. Hence it appears that the dominant character of the shore-line of a region which has recently been uplifted is simplicity—either straightness, or broad flowing curves.

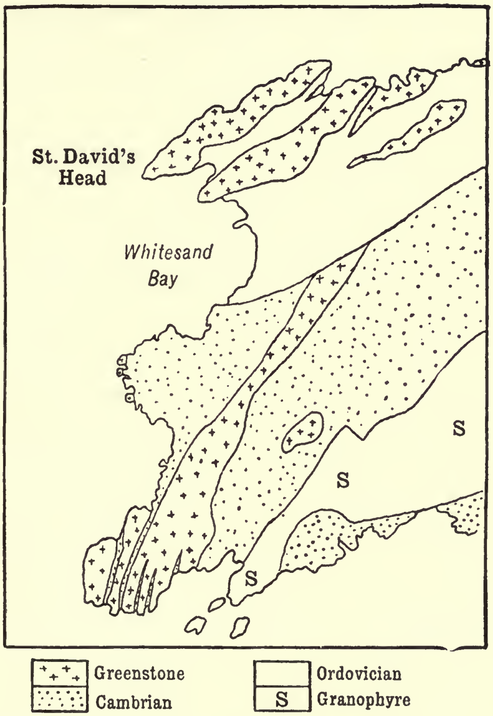


Fig. 51.—Map of the Coast of Pembrokeshire, South Wales.

Showing how the hardness of the rock affects the coast-lines. From the map of the Geological Survey. Scale, 1 inch to 1 mile.

It must not be forgotten, however, that flowing curves of a very similar general outline appear to have been produced in cases where we have no evidence of any recent uplift of importance. The beach of accumulation between two headlands very often shows a remarkably smooth outline, taking the form of a catenary curve. This is due for the most part to wave-action, sometimes assisted by currents. Curved

[1] Davis, *Physical Geography,* 1898, p. 123.

beaches of this sort are found of all sizes, from a few yards up to many miles in length. A striking example on a large scale is the Chesil Beach in Dorset, and small examples can be found on any coast where rocky headlands alternate with small bays indented in softer rock, as on the coast of Pembrokeshire (Fig. 51).

On the other hand, when a land-area of varied relief is submerged, a very complicated coast-line is produced, since the sea encroaches upon and partly fills up the valleys of the land, which are often very long, narrow, irregular and much branched. The form of the shore-line here depends entirely upon the amount of denudation previously undergone by the land, and if a region of mountains and deep valleys is submerged the contours of the coast will be complex in the extreme. No better example of this state of affairs could be cited than the western coast of Scotland, where the long narrow sea-lochs are obviously drowned continuations of the glens of the land, and where the innumerable islands and islets are just as obviously the upper portions of partly submerged peaks. The same is equally true on a still grander scale of the fjords of Norway, and the numberless islands of the Dalmatian coast in the Adriatic.

Coastal inequalities have been explained in two distinct ways by different schools of geologists. The older writers ascribed them all to differential erosion by the sea, while the land remained permanently fixed at its present level. According to this view, bays and gulfs were scooped out of soft rocks, while capes and headlands necessarily consist of hard rocks, and subaerial denudation was supposed to have little influence on the final form of the coast-line. Many modern authors, especially in America, are inclined to go to the other extreme, and to explain everything by the submergence of subaerial topographical forms. There is no doubt, however, that both these agencies must be taken into account, and that no one explanation will fit all cases.

CHAPTER VIII

MARINE DEPOSITS

As we have seen in the preceding chapters, the dominant characteristic of the geological processes occurring on the land is destruction and degradation. On the other hand, the sea is an area of construction and aggradation. The final resting-place of the material derived from the denudation of the land is to be found in the sea, and this material builds up the marine deposits, which may in course of time be uplifted to form new land-areas. But so far as one geological cycle is concerned, the sea is the final destination of the material of the land. In the course of its journey seaward it may find more than one temporary resting-place, such as a lake or a desert basin, but these are only temporary. Deposition in the sea alone can be considered in any sense final.

The processes of denudation as affecting shore-lines have already been considered, and under this heading it became necessary incidentally to refer to the transporting power of waves and currents. It was shown that around every land-area there exists a seaward drift of the finer products of denudation derived from the land, while the coarser material is usually carried backwards and forwards in the immediate vicinity of the shore-line until continued attrition has rendered it sufficiently fine to be carried out to sea below the influence of ordinary wave-action. It follows from the above considerations, that at any given time there is a regular gradation in the size of the fragments as we pass from the shore outwards, and with few exceptions the general rule holds good, that the degree of fineness of the materials composing the marine deposits varies directly as the distance from the shore. The chief exceptions seem to occur where rivers bring down much finely divided detritus, which is often deposited as mud-banks in estuaries.

Zones of Deposition.—It has been found convenient to divide marine deposits, so far as their place of origin is concerned, into three groups, viz. *littoral, shallow-water* and *deep-sea* deposits. These may be broadly defined as follows; littoral deposits are those found between tide-marks, shallow-water deposits are those from low-water mark down to the 100-fathom line, while all below this are classed as deep-sea deposits. At first sight the dividing-line between the shallow- and deep-water deposits seems rather an arbitrary one, but in reality there is a distinct change of character at about this level. As pointed out by Murray and Renard, this is about the average depth at which a great amount of finely divided amorphous material settles on the bottom, which is rarely disturbed by waves and currents, and this is also about the limit of sunlight, and, consequently, of vegetable life. Again, the 100-fathom line marks pretty closely the margin of the continental plateaux, and the slopes to the deeper parts of the oceans are generally abrupt. Beyond the 100-fathom line the deposits are generally fine muds and oozes, while above it sands and coarser sediments prevail. It is, of course, obvious that these three groups must pass into one another by regular gradations, and no distinct line of demarcation can be drawn between them; but for practical purposes the classification is a useful one.

Littoral Deposits.—Some reference has already been made to the general characters of beach-material, and to its behaviour under varying conditions of waves, tides and currents. Generally speaking, littoral deposits consist of rock-fragments which are derived from the land and are undergoing attrition. The bulk of them, however, are still above the critical size proper to the prevailing conditions, so that the tendency of wave-action is still to keep them within the zone of active movement. Littoral deposits may be described in a general way as comprising the coarser forms of marine sediment, such as shingle, pebbles and coarse sand. They often include also abundant shell fragments and other organic remains. It is obviously impossible to give any more detailed description of the lithological characters of beach-material, since the range of variation is so great. A pebble beach or a sand beach may consist of fragments of any rock whatever, or any mixture of rocks of the most widely different types, according to the nature of the land mass from which it is derived. Littoral deposits are rarely *monogenetic*, consisting exclusively of pebbles of only one kind of rock: they are nearly always *polygenetic*, owing to a variety of causes, into which we cannot now enter. Probably the nearest approach to a littoral deposit of uniform origin is to be found in the case of some of the coral islands of tropical regions, which are surrounded by a zone of coral fragments broken off by the waves and undergoing rapid attrition from the same cause.

Shallow-water Deposits.—As before stated, this group includes the sediments laid down on the sea floor between low-water mark and the 100-fathom line; that is to say, the submerged portion of the continental plateaux. The total area covered by them is estimated by Murray at about 10,000,000 square miles. They consist essentially of material derived from the land, the admixture of material of purely organic and marine origin being very variable, according to circumstances. The dominant character of these deposits may be conveniently expressed by the term *sandy*. In the immediate neighbourhood of the land the sediment is coarser, and may often be described as gravel, while in certain localities, and especially off the mouths of large rivers, muds predominate. Since these deposits are laid down for the most part in comparatively shallow water which is within the influence of the agitation caused by waves, tides and currents, they frequently show evidence of such disturbances, in the form of ripple-marks, false-bedding and rapid alternations of sediments of different types, owing to varying conditions. Since the shallow-water zone is that in which marine life is developed to the largest extent, remains of animals and plants are of very common occurrence, and usually extremely abundant; in fact, in some cases organic remains make up the bulk of the deposits. This is especially the case along coast-lines where the water is clear and free from land-derived sediment, since the presence of mud is unfavourable to many of the more important marine animals, such as the reef-building corals. It appears from soundings and dredgings that a great part of the floor of the shallow seas surrounding the British Isles is covered by a deposit which is composed for the most part of comminuted fragments of shells, and is therefore spoken of as *shell-sand*. Again, a very large number of marine organisms have the power of extracting carbonate of lime from the sea-water and building it up into their own tissues. The remains of these calcareous organisms often build up deposits of great thickness, sometimes incoherent, composed of perfect or more or less broken shells, tests, &c., or sometimes in a coherent massive form from the beginning. The most important type of the latter class is afforded by coral reefs in their various forms, which will be subsequently described in detail. It is a generally received opinion that limestones, and other allied calcareous deposits of organic origin, are of deep-water character, but this idea is a mistaken one. With the exception of the calcareous deep-water oozes, to be hereafter described, all the important modern calcareous deposits are being formed in quite shallow water, and in the case of the ancient limestones evidence of deposit near land, within reach of wave and current action, is nearly always to be found.

It would involve much needless repetition to give here a full account of the lithological character of the land-derived sediments of the present day, which exactly resemble the deposits of past ages in so far as their mineral characters are concerned. Full details will be found in the section on the Petrology of the Sedimentary Rocks, wherein are described the characters of the stratified rocks which compose so great a part of the outermost portion of the earth's crust.

Terrigenous Deep-sea Deposits.—Under this heading are comprised the finer kinds of marine sediment, which are deposited in fairly deep water, usually on or near the sub-continental slopes, from the 100-fathom line downwards to a depth of about 2,000 fathoms. They consist of the more finely divided kinds of land-derived material, mixed with a more or less large proportion of matter of organic and marine origin, and they may be grouped under the general heading of *Muds*. Such deposits are estimated by Murray to cover an area of about 18,000,000 square miles, and they vary a good deal in character locally. However, several fairly well-defined types can be recognised, as follows :—

Blue Mud.—This is by far the most abundant type, and is said to cover about 14,000,000 square miles. It is a rather earthy, and not very plastic, material, of a general bluish or grey colour. However, the uppermost layer is always reddish or brown, owing to the presence of ferric oxide, and so it appears that the blue colour is not original, but is due to reduction of the iron oxide by organic matter. Much iron sulphide is present, and the fresh mud generally smells strongly of sulphuretted hydrogen, which must be derived from the decomposition of organisms. The composition varies a good deal ; the amount of calcium carbonate ranges from a mere trace up to 30 per cent., and appears to exist chiefly in the form of tests of foraminifera. The rest is chiefly minute mineral particles, of which by far the most abundant is quartz, but practically all the ordinary rock-forming minerals can be recognised : a little glauconite is sometimes present. Judging from the characters of the ancient sediments which have been preserved to us, blue mud seems to have been a common type in many periods of the earth's history. At the present time its distribution is world-wide, and it is not confined to any special conditions of temperature or latitude.

Red Mud.—Soundings off the coast of Brazil have revealed a considerable area covered by a mud of a brick-red or reddish-brown colour; its composition is very similar to that of blue mud, the chief difference being in the colour, which is due to a very high proportion of ferric oxide. A similar deposit is found in the China Sea, off the mouth of the Yang-tse-kiang, and it appears that this type of mud is formed of material derived from the denudation of great areas of crystalline rocks, igneous and metamorphic, which generally yield a large quantity of iron compounds. The total area covered by red mud is only about 100,000 square miles. It must be carefully distinguished from the Red Clay to be hereafter described, as the two have little in common.

Green Mud.—On the upper edge of the continental slope there is to be found, in some localities, a mud of a greenish colour, which in composition is very like the blue and red muds, but contains in addition a varying proportion of glauconite, a dark-green hydrated silicate of iron and potassium, in the form of rounded grains and casts of foraminifera and other minute animals. Off the coasts of California there is found a so-called 'black sand,' which consists almost entirely of grains of dark-green glauconite, and in many shallow waters the sands have a prevailing green colour owing to the presence of the same mineral. These glauconitic deposits are generally found on exposed coasts without large rivers. One of the best-known examples is the Agulhas Bank, off the Cape of Good Hope, but they also have a wide distribution along the shores of both the Atlantic and Pacific Oceans.

Coral Muds and Sands.—Around the coral islands of tropical regions the floor of the ocean is covered by deposits which consist of comminuted fragments derived from the coral rock of the islands, of varying degrees of fineness, according to the depth and distance from the source of origin. The coarser types found near land may be classed as coral sands, and the finer deposits in deeper water as coral muds. Such calcareous sands and muds cover a large area, especially in the tropical parts of the Pacific, where coral islands are most abundant.

Volcanic Sands and Muds.—Around volcanic oceanic islands and along the coasts of regions of active vulcanicity there are found both sandy and muddy deposits, the materials of which are chiefly of volcanic origin. From these volcanic sands and muds transitions can be traced to all the other types of marine sediment above described. In particular they often graduate into the so-called 'calcareous tuffs,' composed of fragments of volcanic rocks and pumice mixed with remains of foraminifera, &c., embedded in a cement of calcite. Well-known examples occur in the Tonga Islands, Torres Straits, &c.

Pelagic Deep-sea Deposits.—Beyond the lowest limit of land-derived material, which corresponds approximately in most cases with the 2,000-fathom line, the floor of the ocean is covered entirely by deposits of a special character, which are formed for the most part of material which has fallen directly from the surface. As a consequence of their manner of origin these deep-sea, or abysmal, deposits consist chiefly of the remains of organisms which have lived floating or swimming freely in the waters of the open ocean. Such organisms are known as *pelagic*, in contradistinction to the shore dwellers of the continental plateaux. Mineral matter directly derived from the land is absent, and the mineral particles of exceedingly small size which do exist are considered to be of volcanic and cosmic origin, derived from the fine dust which is always floating in the air, as a result of volcanic eruptions and the disintegration of meteorites in the atmosphere. The pelagic organisms which make up the main part of these deep-sea deposits possess skeletons or other hard parts, which may be either calcareous or siliceous. Both calcium carbonate and silica are to a certain extent soluble in sea-water, the former more so than the latter, and this solubility is increased by pressure. Those shells which are very thin in proportion to their size are the most readily dissolved, while thicker and more compact shells resist solution better, since they present proportionately less surface. While these organic remains are sinking slowly after death from the upper waters to the abysmal depths, they are all the while being dissolved, those consisting of aragonite more quickly than those of calcite, so that if the water is of sufficient depth they may never reach the bottom at all. Owing to their lesser degree of solubility, siliceous organisms are found in deeper water than calcareous ones. Hence the formation of these deep-sea or abysmal deposits is essentially a process of separation by differences of solubility.

The following types are recognised by Murray and Renard, but they strongly emphasise the fact that these are rather extreme types, and that innumerable gradations exist between them:—

Globigerina Ooze.—This is perhaps the best known of all the deep-sea oozes, and its constitution and special characters will be described in some detail. It is found chiefly in tropical and warm temperate regions, where the surface is occupied by warm currents which support an abundant pelagic fauna. It is estimated to cover a total area of 50,000,000 square miles, and attains its maximum in the Atlantic. Globigerina ooze is found at an average depth of about 2,000 fathoms, but extends downwards nearly to 3,000 fathoms. The dominant constituents are foraminifera of many kinds: the most conspicuous are those belonging to the genus Globigerina. Besides these, there are to be found fragments of almost all the important groups of marine animals which possess any hard parts. Careful examination under the high powers of the microscope also indicates the presence in large numbers of certain peculiar structures whose true nature was for a long time doubtful. These are called Coccoliths and Rhabdoliths, and may be described as minute disc-like or rod-like bodies, which are considered to be fragments of certain minute and peculiar calcareous algæ, coccospheres and rhabdospheres, which are found to be abundant in the warmer surface waters. These sometimes make up as much as 15 per cent. of the whole. Globigerina ooze varies somewhat in colour; when fresh it may be white, yellowish, pink or grey: when dried it strongly resembles chalk. Besides the calcareous organisms, this ooze contains a variable admixture of siliceous fragments, chiefly radiolaria diatoms and sponge spicules, and a certain amount of mineral matter of inorganic origin. The residue left after treatment of a sample of this ooze with dilute acid exactly resembles the oozes found in deeper water, and in particular the *red clay*, so that description of the mineral fragments may be deferred till the last-named deposit is discussed.

Pteropod Ooze.—This deposit was found by the *Challenger* only in the Atlantic, and it is most typically developed on the ridges which cross the central parts of this ocean at a depth not exceeding 1,400 fathoms.

It consists very largely of the shells of Pteropods, Heteropods and other pelagic mollusks, together with the other constituents of the calcareous oozes. Most of these animals possess notably thin shells consisting of aragonite, so that they are dissolved before reaching greater depths. A pteropod ooze only differs from a globigerinal ooze in the presence of these thin-shelled organisms. This ooze is therefore a dominantly calcareous one. One sample was found to contain 98·47 per cent. of calcium carbonate, and the average of thirteen samples was 79·25 per cent.

Diatom Ooze.—This is a special type of deep-sea deposit which is chiefly developed in the Southern and Antarctic Oceans, where it is estimated to cover an area of 10,000,000 square miles at an average depth of 1,500 fathoms. There is also a patch of it in the northern part of the North Pacific Ocean some 40,000 square miles in area. It is yellowish when wet, white and floury when dry, and consists chiefly of the frustules of diatoms, with radiolaria and sponge spicules. It is thus a distinctly siliceous deposit, but there is usually a small admixture of calcareous foraminifera.

Radiolarian Ooze.—This kind of ooze is confined to great depths; in fact, the samples collected by the *Challenger* came from a greater average depth than the typical red clay. Radiolarian ooze only differs from the true red clay in the presence of a larger or smaller proportion of radiolaria, sponge spicules and diatoms. It is laid down in the *Challenger* report that the deposit should be called radiolarian ooze if it contain more than 20 per cent. of siliceous organisms. A sample from one of the deepest soundings known—4,475 fathoms—in the Pacific contained no less than 338 species of radiolaria. No radiolarian ooze was found in the Atlantic, and its distribution is comparatively limited.

Red Clay.—This is the most widely distributed and the most characteristic of all the abysmal deposits. It is found in most parts of the great oceans at depths exceeding 2,400 fathoms. As its name implies, its general colour is reddish, either of a brick-red or chocolate tint. Some samples are bluish, and some transition forms are grey from an admixture of shells of foraminifera, &c. When fresh it is soft, plastic and greasy, but when dried it becomes very hard. The material of the red clay proper is principally derived from the decomposition of aluminous silicates in the form of mineral and rock fragments spread over the ocean floor as a result of volcanic eruptions, both subaerial and submarine. There is also supposed to be a small admixture of material of cosmic origin, derived from meteorites. Most of the common rock-forming minerals have been recognised, and one of the most abundant constituents is volcanic glass in the form of small fragments of pumice, such as are shot out in abundance into the air during explosive eruptions. There can be no doubt that the chief source of the material of the red clay is the volcanic dust, which is often so finely divided as to float in the atmosphere for months after some of the more violent eruptions, as, for instance, that of Krakatoa in 1883. This dust is carried by winds and air-currents all over the world, and eventually settles down on the surface. It follows from this that the accumulation of the red clay must be a process of almost inconceivable slowness, and in confirmation of this it may be observed that teeth of living and extinct forms of fish have been dredged up together from the surface of the clay. The more conspicuous elements which go to make up the red clay are pellets and nodules of manganese dioxide, the before-mentioned sharks' teeth and ear-bones of whales, and crystals of a zeolitic mineral, phillipsite, the origin of which is still obscure. Sometimes, under special circumstances, evident wind-borne dust particles of terrestrial origin are abundant, as off the west coast of Northern Africa and in the neighbourhood of Australia, both of which are desert regions.

Summary of Marine Deposits.—The different types of marine deposits now known to us may be summarised in the following table. which is adapted from the one given by Murray and Renard :—

LITTORAL DEPOSITS .	Sands, gravels, muds, &c. .	Terrigenous.
SHALLOW-WATER DEPOSITS	Sands, gravels, muds, &c. .	Terrigenous.
DEEP-SEA DEPOSITS .	Coral sands and muds .	Terrigenous.
	Volcanic sands and muds .	Terrigenous.
	Green mud . . .	Terrigenous.
	Red mud . . .	Terrigenous.
	Blue mud . . .	Terrigenous.
	Globigerina ooze . .	Pelagic.
	Pteropod ooze . . .	Pelagic.
	Diatom ooze . . .	Pelagic.
	Radiolarian ooze . .	Pelagic.
	Red clay	Pelagic.

In this table somewhat undue prominence, out of proportion to their geological importance, is assigned to the deep-sea deposits, but this is owing to the difficulty or impossibility of classifying similarly the sediments of shallow water, which show a much greater variation of lithological character; in fact, their varieties are endless, so that they are necessarily included under short comprehensive headings, without any attempt at subdivision.

The Normal Sequence of Deposits.—From what has been said above it will be clear that in passing seawards from the shores of a continental land mass the various types of sediment above enumerated will be encountered in regular order, provided the slope of the sea floor is uninterruptedly in one direction. Slight variations are introduced by differences in the amount of land-derived sediment which reaches the deeper parts of the continental shelf; if such sediment is abundant much mud will there be found, but if the water is exceptionally clear muddy deposits may be almost absent, and their place will be taken by calcareous deposits, such as shell sands and coral reefs, especially in the warmer parts of the sea.

The Forms of Marine Sediments.—The thickness of sediment laid down at any given point will evidently depend on several factors, of which the most important are the amount of material available, the depth of the water, and the character and force of waves and currents. If the supply of land-derived material is abundant the deposit will go on accumulating until its upper surface comes within the reach of wave and current action, and this forms the higher limit. Consequently a greater depth of sediment can accumulate on a steeply sloping shore than on a gentle one. Since the supply of material falls off as we pass farther out to sea, the deposits of terrigenous origin will thin out in that direction, so that on the whole they are wedge-shaped, with the broad end towards the land. But there is also a thinning at the landward end.

FIG. 52.—FORMATION OF SHORE DEPOSITS

Showing their thinning out away from the land.

so that the general form of marine terrigenous sediments must be somewhat as is shown in Fig. 52. The arrangement of the separate strata or layers of which the deposit is composed also depends on similar principles, so that, when regarded on a broad scale, the stratification of marine deposits is not strictly horizontal, but inclined, especially if the submarine slope is at all steep. The general structure of masses of land-derived sediment, if looked at in this way, is seen to have some resemblance to the formation of an embankment by tipping truck-loads of material over the end, which thus grows by addition of successive inclined layers. In this case the level upper surface on which the trucks run is represented by the horizontal or gently inclined lower limit of wave-action (see Fig. 52).

It follows from the foregoing considerations that, on the whole, the moderately coarse-grained shallow-water sediments deposited a short distance below low-water mark will be the thickest, while the muds and other deep-sea deposits are the thinnest; and this is borne out by actual observation of the relative thicknesses of the different types of sediment of the same age among the older rocks. Thick masses of shallow-water strata can often be traced laterally into deep-water muds or clays of moderate thickness, and these again sometimes pass into thin deposits showing a strong resemblance to those of modern abysmal depths.

Coral Reefs and Coral Islands

The most conspicuous and most interesting calcareous formations of the present day are the coral reefs and coral islands which are so widely distributed in tropical regions. Reef-building corals can only live where the temperature of the water never falls below 20° C. (68° F.), hence they are almost confined to the regions enclosed by the parallels of 28° N. and S. Owing to the exceptional warmth of the waters of the Western Atlantic they extend to 32° N. in the Bermudas. Corals do not flourish on the western coast of America; this may be owing either to cold return currents from the poles or to the great amount of mud washed down from the mountains of the Pacific slope. The greatest development of coral reefs is in the Western Pacific and Indian Oceans. Here they occur in vast abundance and exhibit their most characteristic forms.

Types of Coral Reefs.—The structures produced by reef-building corals are usually classified in a general way as fringing reefs, barrier reefs and atolls. Fringing reefs are those which are in visible continuity with the shore; barrier reefs are separated from the shore by a lagoon or channel of greater or less width and depth; while atolls are more or less complete rings of reef, at or near sea-level, without any central island. The origin of fringing reefs is fairly obvious; they are simply platforms extending outwards from the land in shallow water, composed of corals and other calcareous creatures; their upper limit is determined by the level of low tide, since corals cannot live if they are exposed to air and sun for more than a very short time. This reef-platform apparently extends seawards on a talus of its own material, and is often bounded on the outer side by a raised rim, consisting to a very large extent of nullipores and other calcareous algæ. The structure of the reef is frequently cavernous, and it is generally traversed by open channels opposite the mouths of streams; at these points the conditions are unfavourable to the growth of corals owing to the presence of fresh water and mud.

The origin of barrier reefs and atolls has given rise to a great deal of controversy, and even now perhaps the question is hardly settled. The essential structure of a barrier reef is very much like that of a fringing reef, except that it is separated from the land by a lagoon or channel. Barrier reefs vary greatly in size: they may be a few yards or several miles in width, and of almost any length. The Great Barrier Reef off the coast of Queensland is the largest known example. It is some 1,200 miles long and sometimes 10 miles wide, and is separated from the shore by a channel up to 90 miles in width.

Atolls.—Still more characteristic and peculiar are the atolls, which are more or less complete rings of reef enclosing a lagoon, without any central island (Fig. 53). The pictures of atolls in popular books are rather misleading, since they generally represent a continuous circular ring of land of uniform height and symmetrical structure. True atolls are rarely circular, and hardly ever possess a continuous ring of land above sea-level. Generally they consist of a submerged reef-platform of irregular shape, and on the rim of this arise a greater or smaller number of detached islands, which are often more or less continuous or only separated by shallow channels. As a rule, land is more continuous on the windward side, and the leeward side is often completely without islands. Besides these shallow channels there are generally one or two passages into the lagoon deep enough for ships to enter. Only one or two good instances of completely closed atolls are known, e.g. Niau in the Paumotu group, and Clipperton Atoll[1] in the North Pacific. The depth of the lagoon rarely exceeds 30 fathoms, but some are known as much as 50 fathoms deep. The dimensions of atolls are very variable, from a mile or so up to 90 miles in diameter. Frequently small atolls are arranged around the periphery of a large submerged platform, as in the Maldives.

Fig. 53.—Limestone Atoll, Fulanga, of the Eastern Group of Fiji Islands. (After Stanley Gardiner.)

The structure of a typical atoll is somewhat as follows. In the centre is the lagoon with a flat floor, rising slightly near the margin

[1] Wharton, *Q.J.G.S.*, vol. liv., 1898, p. 228.

towards the reef, which rises abruptly, often forming a submerged cliff a few feet high. The reef itself is essentially the same in structure as the barrier reefs above described, usually with a raised rim on the seaward side. Outside the actual ring of the reef comes a very rough surface, sloping down gently to a depth of about 40 fathoms, the so-called reef-platform. This passes abruptly into a *steep*, at an angle often exceeding 50° and sometimes as high as 75°. At about 140 fathoms this steep begins to pass gradually into the contour of the sea-bottom.

Origin of Atolls: Darwin's Theory.—The earliest explanation offered to account for the existence of atolls was that they were formed around the craters of submarine volcanoes. However, this was soon seen to be inadequate, although it is undoubtedly true in one or two cases, e.g. Totoya and Thombia in Fiji. The whole subject was investigated by Darwin[1] during his memorable voyage in the *Beagle*, and on the observations then made he founded a theory which was widely accepted. According to Darwin, fringing reefs, barrier reefs and atolls were three successive stages in the growth of corals round a slowly sinking land-area, so that the growth of the reef was able to keep pace with the subsidence.

It is a matter of observation that the growth of the reefs is most active on the outer margin; and Darwin supposed that, as the island sank, the growth of the corals was upward, and to a certain extent outward, on a talus slope of their own débris. Commencing with a fringing reef, as the island sinks and becomes less the reef becomes more and more distant from the shore, first forming a barrier reef with a channel inside it, and eventually, when the whole island has disappeared beneath the waves, a circular ring of coral is left, with a shallow lagoon inside it, forming an atoll.

Murray's Theory.—However, later investigations, and especially observations during the voyage of the *Challenger*, revealed some features difficult to explain on the simplest form of the subsidence theory. Numerous instances were found of recent coral reefs at all elevations up to 1,000 feet above sea-level, and it was clear that the whole of the vast area over which coral reefs are found was not undergoing uniform submergence. Sir John Murray[2] put forward an alternative theory, which supposed that reefs and atolls had been built up from the tops of submarine banks, former volcanic islands, consisting mainly of loose ash reduced to the lower limit of wave action, which is about thirty fathoms. It was known that such banks have actually been formed

[1] Darwin, *Coral Reefs*, 3rd ed., 1889.

[2] *Proc. Roy. Soc. Edin.*, x., 1880, p. 505; '*Challenger*' *Report*, Narrative, vol. i., p. 781; *Nature*, vol. xxxix., 1888, p. 424.

in various parts of the world during the last hundred years. Murray accounted for channels within barrier reefs and lagoons within atolls by solution of the less actively growing or dead inner portions, assisted by tidal scour and currents and the activity of boring organisms. Admiral Wharton attributed the higher level of the outer part to increased growth of the seaward surface.

Recent Researches on Coral Reefs.—At this point the controversy remained for some years; but interest subsequently revived, and the question was reopened by the work of Agassiz, Guppy, Wharton, Lister, Sollas, Gardiner, and Andrews.[1] It was found that a large share in the actual building of the reef must be attributed to the calcareous algæ, and especially to the nullipores. These flourish specially on the outer raised rim, which, indeed, was noticed by Darwin and Dana. Then, again, it is believed that reef-building corals feed mainly by means of commensal algæ, which require light, thus limiting their growth to a zone in which sunlight penetrates.

Funafuti.—In the early nineties a committee of the Royal Society investigated the structure of a typical atoll—namely, Funafuti—in the Indian Ocean (see Fig. 54). Borings were put down to a depth of about 1,100 feet, passing entirely through coral rock, more or less converted to dolomite. This great thickness is in itself indicative of subsidence, but it is not conclusive, since it was not possible to determine with certainty whether the rock consists of coral in the position of growth or of talus material.[2] This difficulty is largely due to the extensive chemical changes that have taken place in the rock, obscuring the structure.

Raised Coral Reefs.—Explorations undertaken in many parts of the Pacific have proved the existence of coral reefs of recent date at all elevations up to at least 1,000 feet above sea-level. Such occur, for example, extensively in Fiji, as shown by Foye, and in the Tonga Islands, as described by Lister.[3] This group consists of platforms at three distinct heights, at approximately 140, 300, and 500 feet above sea-level. One small island has a remarkable basin-shaped top with a flat rim, and is obviously a raised atoll. In the islands of Kambara and Wangava,

[1] Agassiz, *Proc. Roy. Soc.*, lxxi., 1903, p. 412. Guppy, *Scottish Geogr. Mag.*, v., 1889, p. 281. Wharton, *Nature*, vol. lv., February 25, 1897, p. 390. Lister, *Q.J.G.S.*, xlvii., 1891, p. 590; *Proc. Roy. Geogr. Soc.*, March, 1890, p. 157. Sollas, *Nature*, lv., 1897, p. 373. Gardiner, *Proc. Inter. Congr. Zool. Cambridge*, 1898, p. 119; *Am. Journ. Sci.*, xvi., 1903, p. 203; *Proc. Camb. Phil. Soc.*, ix., p. 417; *Nature*, vol. lxix., February 18, 1904, p. 371. Andrews, *Monograph of Christmas Island*, 1900.

[2] 'The Atoll of Funafuti,' *Report of the Coral-reef Committee of the Royal Society.* London, 1904.

[3] Lister, *Q.J.G.S.*, xlvii., 1891, p. 590.

in the Lau Islands, the south-east portion of the Fiji group, there are raised rims of this kind 260 and 300 feet high respectively on the inner side. Another very interesting case is Christmas Island, described by Andrews.[1] This is the flat summit of a volcano, more than 15,000 feet high from its base on the sea-floor, of which nearly 1,200 feet is above sea-level. Forming the upper part of the island are limestone terraces, ranging from Eocene to Recent, with volcanic rocks below, and also

Fig. 54.—Section through Pava Island, Funafuti. (After Stanley Gardiner.)

a, Rim; *b*, Reef flat; *c*, Rough zone, with pinnacle; *f*, Lagoon platform.

interstratified with their oldest members. The succession of events seems to have been as follows: First a gradual depression, leading to the formation of the Tertiary limestones; then a period of rest followed by successive elevations, giving rise to the present terraced structure. A long pause between the downward and upward movements led to the atoll condition for a while.

American Investigations on Coral Reefs.—During the last few years American geologists have devoted much attention to the coral problem, and have examined in detail many reefs and coral islands both in the

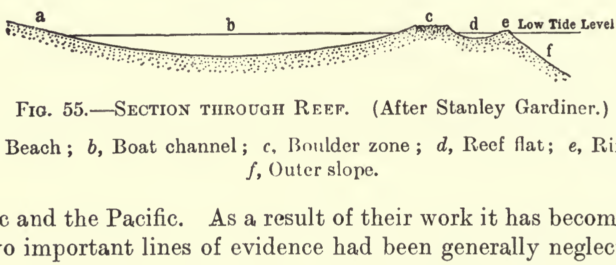


Fig. 55.—Section through Reef. (After Stanley Gardiner.)

a, Beach; *b*, Boat channel; *c*, Boulder zone; *d*, Reef flat; *e*, Rim; *f*, Outer slope.

Atlantic and the Pacific. As a result of their work it has become clear that two important lines of evidence had been generally neglected by writers on the subject, most of whom were biologists rather than geologists. These two factors are the form of the coast-line of the land bordered by barrier reefs, and the character of the contact between the material and the underlying solid rock. It was noticed by Dana as long ago as 1849 that in most cases the coast-line of the land behind a barrier reef, such as Queensland, or the coast of an island surrounded by such a reef, is very irregular when examined in detail. In such cases the inlets are obviously *drowned valleys*, and in a locality where glaciation is excluded such drowned valleys are a definite proof of submergence.

[1] Andrews, *A Monograph of Christmas Island*, 1900.

J. J. Lister, photo.

(I) RAISED CORAL REEF FORMING UNDER-CLIFF: WEST SIDE OF EUA, TONGA ISLANDS.

J. J. Lister, photo.

(II) CORAL REEFS AT DIFFERENT LEVELS: RAISED REEF IN THE FOREGROUND, MODERN REEF IN THE DISTANCE. SOUTH OF TONGATABU, TONGA ISLANDS.

With regard to the contact of reef and rock, it may be pointed out that on the submarine bank theory this contact ought to be horizontal. This fact is, of course, difficult to demonstrate, and information can only be obtained in the case of elevated reefs, where the contact is now accessible. Davis[1] has shown that in a large number of instances examined by him the base of the reef material is steeply inclined and rests on a deeply eroded base of older rocks; that is to say, that there is an unconformable junction with overlap such as could only be produced in an area undergoing submergence. The evidence from these two considerations therefore strongly supports Darwin's theory.

It has been pointed out that submergence of land may be due to other causes besides actual downward movement. The same effect would be produced if the land remained stationary and the sea-level rose. This rise of the sea might be produced by elevation of land elsewhere, or by actual addition of water to the ocean. In accordance with this last possibility, Daly has formulated a theory that the submergence of the Pacific Islands was due to the return to the ocean of water formerly locked up as land-ice during the Glacial period.[2] This would, however, necessitate a uniform submergence everywhere, which has not been established. In fact, the contrary is the case: it is admitted by all writers that coral reefs occur at all levels, and that their distribution has been determined largely by earth-movements of local distribution and variable direction. The Pacific is a highly volcanic region, and most of the Atlantic reefs are near the volcanic chain of the West Indies and Central America.

It is, of course, obvious that the arguments from embayed coastlines and unconformable contacts cannot be applied directly in explanation of atolls without central islands, since neither phenomena can there be seen. But atolls are so like the barrier reefs round islands that the argument from analogy probably holds good, and the same explanation may be applied.

It may be concluded, therefore, that coral reefs are formed during submergence of land, and that Darwin's theory now holds in all essential points with such modifications as are required by later work. It is clear that the submergence was not uniform, as he supposed, but very local, and in some cases it can be shown that single groups of islands have been tilted about an axis; thus the occurrence of local raised reefs presents no obstacle to the acceptance of Darwin's theory in its most general form.

[1] Davis, *Science Progress*, vol. xiii., 1919, pp. 420-444; *Bull. Geol. Soc. Amer.*, vol. xxix., 1918, pp. 489-574.

[2] Daly, *Proc. Amer. Acad. Arts and Sciences*, vol. li., pp. 157-251.

CHAPTER IX

THE SEDIMENTARY ROCKS

Introductory.—As a result of the processes of denudation and deposition briefly described in the foregoing chapters, there have been accumulated masses of sediment which, in course of time, are more or less completely consolidated and converted into what are popularly known as *rocks*. All masses which are formed in this way are known as the *sedimentary* rocks, in contradistinction to the *igneous* rocks, which are formed by consolidation from a state of fusion.

Classification of the Sedimentary Rocks.—The sedimentary rocks can be classified in various ways, of which the most important are—

(*a*) Classification according to origin.

(*b*) Classification according to composition.

Unfortunately, neither system is altogether satisfactory owing to the existence of numerous transition forms from one type to another, but on the whole it is found that composition affords a more satisfactory basis for classification than origin, as it entails less repetition.

So far as the lithological character of the sediments is concerned, the commoner types may be divided into several fairly well-defined groups, each of which possesses certain distinctive chemical and mineralogical characters, and in many cases these differences of character correspond more or less closely to differences of origin. It must not be forgotten, however, that innumerable transitional forms exist, obscuring the boundaries between the various classes.

(1) **Arenaceous or Sandy Rocks.**—This group includes the more coarse-textured sediments, which have been laid down either in shallow water, salt or fresh, or under terrestrial conditions. They consist of particles, of minerals or rocks, which are sufficiently large to be easily distinguishable by the naked eye, and in some members of the group the individual constituents may be of considerable size, measurable by inches or even by feet. These coarser types are not, strictly speaking, *sandy* rocks, but may be conveniently included here, since they are formed

from gravel, shingle and other accumulations laid down under the conditions above specified. The raw materials of the arenaceous rocks can therefore be divided into two classes—*sands* and *gravels*—and the different rock-types recognised in the group are derived from these by processes of consolidation.

Beds of sand do not usually remain in a loose incoherent state for any considerable length of time, but are consolidated into coherent masses—*rocks* in the popular sense of the term. It must not be forgotten, however, that in a strictly scientific sense any aggregate of mineral particles is a rock, whatever may be its state of coherence. The consolidation of loose sands into rocks is effected by the deposition of material in the spaces between the grains, and more or less firmly attached to them. This interstitial material is commonly deposited from solution in percolating water, and is spoken of as *cement.*

The most common cementing substances are silica, carbonate of lime, and some forms of iron oxide, either anhydrous or hydrated. These are spoken of as *siliceous*, *calcareous* and *ferruginous* cements respectively. According to the character of the mineral particles and the nature of the cement various special names are applied to the different rock-types.

Sand.—This name is applied to the loose incoherent aggregates of mineral particles of sufficient size to be easily visible to the naked eye. Sand-grains may be either *simple*, consisting of one crystalline individual or part of such; or they may be *compound*, composed of aggregates of crystals of one or more minerals; the latter kind of grain may also be defined as a rock-particle. Sands also often contain shells and other structures of organic origin, either whole or broken, and often finely comminuted. By far the most abundant of the minerals composing all ordinary sands is quartz, since this substance is hardly affected by any of the ordinary weathering agents, whereas most of the other common rock-forming minerals are easily destroyed by weathering. After quartz, the most abundant constituents of sands are flakes of white mica, grains of felspar, and more or less rolled crystals of hornblende, augite, magnetite and many of the other minerals of the igneous and metamorphic rocks. Since the minerals of the latter groups have, as a whole, a considerably higher specific gravity than quartz or felspar, they are easily separated for examination by means of dense fluids in which the quartz and other light grains float, while those of a higher density than the liquid sink to the bottom. The study of the heavy minerals of the sedimentary rocks has of late years become an important and fruitful branch of petrology,[1] and it has in some cases thrown a considerable amount of light on the sources from which the

[1] H. H. Thomas, *Q.J.G.S.*, 1902, p. 620; and 1909, p. 229. *Min. Mag.*, vol. xv., 1909, p. 241.

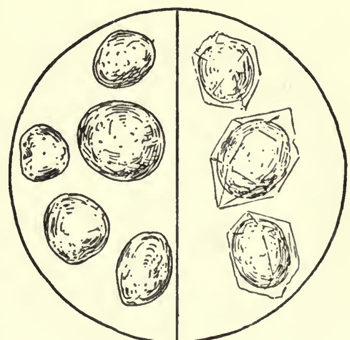
materials were derived. Some of the most important of the minerals which have been identified by this method are zircon, tourmaline, garnet, cassiterite, rutile, anatase, brookite, andalusite, kyanite, sillimanite, staurolite, fluor-spar, sphene, ilmenite and biotite.

FIG. 56.—MODERN BEACH SAND.

a, Quartz; *b*, Tourmaline; *c*, Magnetite; *d*, Zircon: *e*, Glaucophane.

It is unnecessary to give any detailed account of the compound grains which may occur in sands, since they may consist of fragments of rock of any kind whatever; however, as would naturally be expected, the most abundant are fragments of the hardest rocks, and especially rocks in which quartz is a prominent constituent (see Fig. 56).

The size and form of sand-grains vary according to the conditions under which they are formed and it is scarcely possible to lay down any definite rules; but, broadly speaking, it may be said that sands formed in water usually consist of subangular grains, that is, grains of more or less angular form with their corners rounded off: in desert sands, on the other hand, the grains are often very completely rounded, both large and small alike: such are often spoken of as millet-seed sands (Fig. 57). In some water-formed deposits in which the grains vary a good deal in size, it is often noticeable that the larger grains are much more rounded than the smaller ones. It is generally stated that sands of glacial origin possess sharply angular grains, owing to the absence of any rolling motion.



A *B*

FIG. 57.

A, Millet-seed sand-grains; *B*, Grains from the Penrith Sandstone, showing secondary growth of silica, with crystal faces, in optical continuity.

When a sand is consolidated into a rock by a process of cementation, different names are applied according to the nature of the cement, the amount of hardening undergone and the nature of the constituent grains.

Sandstone.—When the amount of cement is small, so that the rock is quite soft and crumbly, it is called a *sandstone*. The cement is either silica or iron oxide, or a mixture of the two. White sandstones have a siliceous cement, while the yellow and brown colours so commonly seen are due to a cement of iron oxide. Another common type is red sandstone, and in these it is often observed that each grain is coated by a thin pellicle of red ferric oxide. On boiling with dilute acid the iron oxide is dissolved and colourless grains of quartz and other minerals are left behind. These conspicuously red sandstones usually seem to be of desert origin.

Quartzite.—When a rock consists chiefly of grains of quartz cemented by silica into a hard continuous mass, it is commonly called quartzite (see Fig. 58). The same name is also applied to sandstones recrystallised by heat into a mosaic of quartz grains without definite outline; hence some confusion inevitably arises.

Grit.—This name was originally applied to hard rocks consisting of sand grains mixed with small pebbles; such rocks break with a very rough surface and are suitable for millstones. Of late years the term has been extended to include almost any type of hard arenaceous rock, irrespective of texture, such as are so common in many of the older rock-formations.

Calcareous Grit.—When the cement consists of calcite, so that the rock is composed of grains of quartz, &c., embedded in crystals of calcite, which often show their characteristic cleavages when broken, it is called a *calcareous grit.*

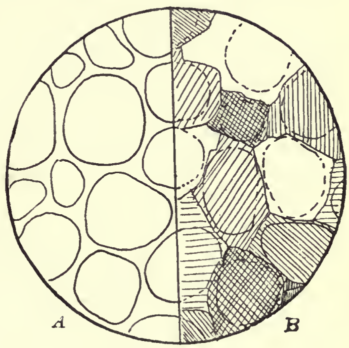


Fig. 58.—Quartzite.

A, In natural light; *B*, Between crossed nicols. The interspaces between the grains are filled with a secondary outgrowth of quartz in optical continuity.

The shading is diagrammatic, indicating different interference tints.

Arkose.—This name is applied to a sandstone or grit which contains a large proportion of felspar; the cement is usually siliceous. Arkoses or felspathic grits often result from the denudation of large areas of crystalline rocks of igneous or metamorphic origin.

Greywacké.—This is a somewhat old-fashioned term often applied to the grey or greenish grits which are so characteristic of the older sedimentary formations. They usually contain a good deal of material of volcanic origin, and they graduate into the true volcanic ashes.

Flags.—In many formations there are found rocks of the arenaceous class which contain a large proportion of thin flakes of white mica. These flakes generally lie parallel to the bedding planes, and in consequence the rocks split readily into slabs parallel to these planes. These are called *flags*. This name is also applied to many thin-bedded sandstones with little or no mica, which break up readily into flat slabs.

The above list includes the more important rock-types which are formed by the consolidation of sands in the usual sense of the term, but as before stated, it is convenient to include under this group certain rocks which are formed by the cementation of still coarser sediments—gravel, shingle, pebbles or scree material. These may be placed under two headings; if the fragments are rounded the resulting rock is called a *conglomerate*, and if angular a *breccia*. These two terms are employed quite generally, irrespective of the actual nature of the pebbles or fragments composing the rock, which may be siliceous, argillaceous, calcareous or of any other composition. Conglomerates are specially characteristic of ancient shore-lines, and consequently frequently accompany unconformities. Breccias are most commonly formed under terrestrial conditions, and especially in desert regions, where the fragments escape rolling by water action.

(2) **Argillaceous or Muddy Rocks.**—In this group are included the finer kinds of land-derived sediment laid down in water of moderate depth; the character and distribution of the modern deposits of this class have already been referred to (see p. 124). At their lower limit the sandy deposits of shallow water graduate down into muds, and the only essential difference between the two classes is in the state of division of the material. In the true argillaceous rocks the particles are so small as to be individually invisible to the naked eye. As a result of consolidation and pressure various secondary structures are induced, giving rise to more or less distinct types of sediment, as hereafter described.

Mud.—The mineralogical constituents of a fresh mud are of very variable character, and, owing to the very small size of the particles, usually difficult to determine. It appears, however, that most muds consist essentially of minute particles of the ordinary rock-forming minerals, of which quartz and mica are by far the most abundant. The proportion of mica is usually higher than in the sandy rocks, since owing to their flattened form flakes of mica remain longer in suspension than the more compact grains of quartz, and are therefore carried farther from the shore. Felspar also is fairly common, and minute crystals of zircon and other rarer minerals also occur, just as in sands. Besides these constituents most muds contain a good deal of material of organic origin, especially of a carbonaceous nature. Reference has already been made to the characteristic colouring of the muds of deep water (p. 124). Besides these constituents, most argillaceous rocks contain a good deal of material in an exceedingly fine state of division, which was formerly regarded as kaolin (a hydrated aluminous silicate), but it is now believed to be a very finely divided micaceous substance, probably of secondary origin.

Clay.—A very common type of sediment, especially among the younger formations, is one which is formed by the compression and partial drying of a mud. This is known as a *clay.* The compression is usually effected by the weight of overlying strata, and it is accompanied by loss of water, so that the material decreases somewhat in bulk and becomes plastic. In true clays no particular structure is developed, and the mass is usually traversed by irregular cracks due to shrinkage, so that it breaks with a more or less conchoidal fracture. The colours of clays depend on the state of oxidation of the iron which they contain. Besides the true sedimentary clays there are other special types of argillaceous rocks of different origin. Some of the most important of these are—China-clay, formed by the decomposition of granite *in situ*; Laterite, a reddish clay, formed by decomposition of basic lavas in tropical climates; Loess, a pale calcareous clay found in Central Europe and Asia over large areas, probably formed by wind-blown dust; Boulder-clay, an accumulation of glacial origin, consisting of pebbles and boulders, often scratched, embedded in a matrix of clay and finely divided rock-material.

Mudstone.—When a clay has been so much hardened by drying and compression that it has lost its plasticity, it is known as a *mudstone.* A true mudstone shows no definite structure, except that it is often traversed by joints in various directions, owing to shrinkage.

Shale.—When an argillaceous rock shows a tendency to split readily into thin slabs parallel to the original bedding, it is called a *shale.* This structure is known as *lamination* (see p. 13). It appears that besides the mechanical rearrangements involved in the formation of a shale, there is also a considerable amount of mineralogical change, and especially production of a secondary micaceous mineral, which facilitates the splitting. Many clays, mudstones and shales contain a good deal of iron pyrites, often in crystals of considerable size. This mineral is formed by reduction of iron oxides by organic matter which generally contains a good deal of sulphur, and the dark colour of many shales is supposed to be due to finely disseminated iron sulphides.

Slate.—Very many argillaceous rocks, especially among the older formations, have undergone a further change in the development of new planes of division, or cleavage planes. Such rocks are known as *slates*, and will not be further described here. The general character of *cleavage* has been dealt with in the introduction, while the rocks themselves strictly come under the heading of metamorphism (see Chapter XIV.)

(3) **Calcareous Rocks.**—Under this heading are included a large number of rock-types of diverse origin and varying character, which

agree in the fact that they contain a notable proportion of calcium carbonate. Many of the calcareous rocks are of organic origin, being composed for the most part of the more or less altered remains of animals and plants which possess a calcareous shell or skeleton. Since these are almost exclusively inhabitants of the sea or of fresh water, it follows that the calcareous organic sediments are chiefly of aqueous origin. Besides these organic sediments, some important types of calcareous rocks are formed by various inorganic processes, both mechanical and chemical, as will be hereafter explained. Many of the calcareous rocks differ from those of the classes hitherto described in that they do not pass through an unconsolidated stage, but are originally deposited in a coherent form. This statement applies to rocks of both organic and inorganic origin. The great majority of the rocks of this group come under the somewhat vague general designation of limestones, but special names are also applied to many of the varieties, and as a matter of convenience some rocks which are not, strictly speaking, calcareous are also included here.

Calcareous Muds and Oozes.—Perhaps the simplest examples of unconsolidated calcareous deposits are afforded by the coral muds and deep-sea oozes which are being formed at the present day in the deeper parts of the oceans and in the regions surrounding coral islands. These have already been described in some detail, and need no further reference here (see p. 126). In many fresh-water lakes also there are to be found deposits of a muddy nature containing a considerable proportion of calcium carbonate.

Shell-sand and Shell-banks.—In the shallow seas surrounding land-areas there are frequently to be found enormous accumulations of dead shells, either whole or broken. Such shell-banks and shell-beaches are common on the Atlantic coasts of Britain, and especially on the coast of Holland, and Mr. F. W. Harmer has shown that these accumulations depend on the direction of the prevailing winds, which in this area blow most persistently from the south-west and west. Dredging operations have also shown that the floor of the Irish Sea, the English Channel, and other seas on the continental platform, is covered with a deposit consisting very largely of finely comminuted shells, mixed with a greater or less proportion of sandy sediment. These deposits are commonly known as shell-sands.

Shelly Limestones.—When masses of whole or broken shells, such as were described in the preceding paragraph, are cemented into a solid rock they form shelly limestones, such as are common at many stratigraphical horizons. The cement in this case may consist either of finely divided calcareous mud, formed at the time of deposition and subsequently hardened by drying, or of crystalline calcite deposited at a later date by percolating water. There is often a considerable amount of ferruginous material in such a cement, and to this is due the yellowish or brownish colour of certain limestones. Shell-banks, such as those now forming on the British and Dutch coasts, give rise to beds like some of the Pliocene 'Crags' of Norfolk and Suffolk, which are masses of shells more or less consolidated by a calcareous or ferruginous cement.

Coral Rock.—This is a variety of limestone which consists to a large extent of the remains of reef-building corals and other organisms. The character, distribution and origin of modern coral-reefs and coral islands has been discussed in detail in an earlier chapter, and it must suffice here to say that fossil coral-reefs of an essentially similar character occur to a considerable extent among the stratified rocks of various periods.

Crinoidal Limestone.—The Crinoidea, a class of the phylum Echinoderma, play a small part at the present day, but in the past they were of great importance as rock-formers, and enormous masses of limestone were built up to a great extent of their remains. A notable example is afforded by the Carboniferous limestone of Britain. Modern echinodermal deposits are, however, being formed to a considerable extent in the Irish Sea.[1]

Chalk.—This name is applied to a peculiar rock-type which is characteristic of the upper part of the Cretaceous formation of North-western Europe and elsewhere. It is a white, grey or yellowish rock of varying hardness, and usually of fine texture. It varies somewhat in composition, but usually consists to a large extent of finely divided calcareous mud with a greater or less proportion of recognisable organic remains, including Foraminifera, especially *Globigerina*; minute fragments of molluscan shells, especially *Inoceramus*; together with fragments of corals and sponge spicules, both siliceous and calcareous. Foreign detrital matter is not abundant, and chalk often consists of nearly pure calcium carbonate.

Marl.—This rock is somewhat intermediate in composition between the argillaceous and calcareous rocks; it includes various types of calcareous clays and argillaceous limestones. Marls are very commonly laid down in fresh-water lakes, and often contain abundant remains of gastropods, crustacea and fresh-water algæ.

The Microscopic Structure of Limestones.[2]—Most of the fragments of calcareous organisms which go to build up limestones possess peculiarities of structure which enable us to assign them to their proper zoological position. The most important of them are Foraminifera, calcareous Algæ, Corals, Echinoderms, Polyzoa, Brachiopods, Lamellibranchs, Gastropods, and Cephalopods. Calcium carbonate possesses

[1] Clement Reid, *Brit. Assn. Rep.*, 1895, p. 464.

[2] Sorby, *Presidential Address to the Geological Society*, 1879.

two distinct crystalline forms, calcite and aragonite, with different physical properties. Aragonite is unstable under ordinary conditions, and is frequently either recrystallised as calcite or removed altogether by solution. Hence aragonite shells are often represented by mosaics of recrystallised calcite or by hollow spaces. In course of time the calcite of limestones also undergoes more or less recrystallisation, so that the original structure is often obscured; and some limestones have been more or less completely recrystallised, or converted into marble, without the help of any metamorphic agencies. For an account of the effects of heat and pressure (metamorphism) on limestones, see p. 260.

Most limestones contain more or less detrital matter of inorganic origin, according to the conditions under which they were formed; these impurities are usually of a sandy nature, consisting of grains of quartz, felspar and other minerals of the mechanical sediments. Glauconite also is not uncommon.

Oolitic Structure.—Many large masses of limestone possess a peculiar and characteristic structure, being composed of rounded grains having somewhat the appearance of the roe of a fish, and from this the name *oolite* is derived. When the grains are of considerable size, as big as a pea, the rock is known as *pisolite.* Oolitic grains usually consist of concentric coats of calcareous material, either calcite or aragonite, arranged round a nucleus, which may be either a minute shell fragment, a sand-grain, or merely a pellet of calcareous mud. Besides the concentric coats there is often a more or less conspicuous radial arrangement of the minute elements of the grain. Sometimes the grains are compound; that is, two or more small grains may be enclosed in one outer coat. Sometimes the material has been recrystallised, so that the concentric and radial structures are destroyed, and it appears that aragonite grains are often recrystallised as calcite. Oolitic grains appear to be formed in several different ways. Some are evidently concretionary structures of mechanical origin, due to the deposition of layers of calcium carbonate round a nucleus in a saturated solution. This process probably goes on in shallow water, under the influence of current-action, which assists the production of rounded forms. It is clear, however, that in many cases calcareous algæ play an important part in their formation, as for example in the Sprudelstein of Carlsbad and the oolitic sand of the Great Salt Lake. Many grains show under the microscope layers of tubular structures, which are referred to a problematical organism, *Girvanella,* which may be a simple form of calcareous alga.

Limestones of Mechanical Origin.—Certain beds of limestone which possess a nodular or pisolitic structure appear to be of mechanical origin in their present form. They are composed of fragments derived from pre-existing limestones, and are not due directly to organic agency.

They are therefore to be regarded as shallow-water sediments formed in areas where large masses of calcareous rocks are undergoing denudation. Such appears to have been the origin of the Cornstones of the Old Red Sandstone of the Welsh border, and probably also of the Lias limestones of Dorsetshire, where the rapid alternation of thin beds of shale and limestone almost precludes the possibility of direct organic agency.[1] Probably many calcareous beds, showing little or no definite structure, were formed from calcareous mud of detrital origin.

It has been pointed out by Professor Skeats that some idea of the conditions under which a limestone has been formed can be obtained from the proportion of non-calcareous insoluble residue present in the rock. A chemically pure limestone has been formed under 'coral-reef' conditions, beyond the reach of land-derived sediment: a limestone with more than 1 per cent. of insoluble residue has been formed either in deep water or as a detrital deposit, the nature of the residue indicating under which of these conditions it was formed: shallow-water limestones contain sand-grains, while deep-water limestones contain material of the types which have been before described as occurring in modern deep-sea deposits.

Travertine and Calc-sinter.—Calcium carbonate is almost insoluble in pure water, but when it is acted on by water containing carbon dioxide a reaction occurs, and a bicarbonate is formed, thus—

$$CaCO_3 + H_2O + CO_2 = H_2Ca(CO_3)_2$$

This bicarbonate is soluble in the water to a much greater extent than the simple carbonate. Since all natural waters contain carbon dioxide, the waters percolating through limestone rocks become saturated with the bicarbonate. The amount dissolved also increases with the pressure. It is to be noted that heat diminishes the solubility, since the carbon dioxide is driven off and the normal carbonate is again formed. The waters of many springs become charged with the bicarbonate under considerable pressure, and when the spring reaches the surface the release of pressure, together with a certain amount of evaporation, causes the normal carbonate to be reformed and deposited. This gives rise to a spongy calcareous deposit often known as *tufa*. In the same way the water which drips from the roof of limestone caverns undergoes evaporation and deposits carbonate of lime. This gives rise to peculiar forms, generally having an elongated shape and concentric structure. When these hang down from the roof of the cave they are known as *stalactites*, and the corresponding structures rising from the floor are called *stalagmites*.

The largest and most important of this class of deposits are those

[1] H. B. Woodward, *Proc. Geol. Ass.*, 1903, p. 327.

formed by hot springs, and to these the general name of *travertine* or *calc-sinter* is applied. In this case the process of deposition is not merely one of evaporation, but the separation of the carbonate of lime in the solid form has been shown to be effected by algæ, which live in the heated water and deposit the carbonate in their tissues. The exact way in which this is effected is not understood. One of the best examples of this type of sinter is afforded by the Mammoth Hot Springs in the Yellowstone Park. Large deposits of travertine also occur at Rome and in other parts of Italy. The Sprudelstein of Carlsbad is also formed by algæ, and this shows a very perfect example of oolitic structure, in which the grains consist of aragonite.

In some cases it is believed that calcareous deposits of this kind are due to actual chemical reactions between two solutions, as at Mono Lake in California, and this process may have occurred in some of the salt lakes of past ages.

Dolomite Rock or Magnesian Limestone.—Closely allied to the true limestones is a rock which consists essentially of the carbonates of lime and magnesia. This is known as *dolomite* (more correctly *dolomite rock*), or sometimes magnesian limestone. The magnesium carbonate occurs in varying proportions up to a maximum of about 44 per cent. This corresponds to the molecular ratio $CaCO_3 : MgCO_3 = 1 : 1$, and a rock of this composition consists entirely of the mineral dolomite, which is a double carbonate having the formula $CaMg(CO_3)_2$. A lower proportion of magnesium carbonate indicates an admixture of calcite or aragonite with the dolomite.

The origin of dolomite rock has given rise to much discussion. In a few cases, as in the Raibl beds of the Tirol, beds of dolomite are found associated with gypsum in such a way as to leave little doubt that they are due to precipitation during concentration of sea-water by evaporation in closed areas. But it is now generally accepted that in the majority of cases these rocks were originally normal limestones, with only a small proportion of magnesium carbonate, and it is a significant fact that many recent coral-reefs are in parts dolomitic.

Most large masses of limestone are more or less dolomitised; and in some cases the process appears to be almost complete, as, for instance, in the Tirol, where beds of dolomite rock of Triassic age reach a thickness of several thousand feet. These beds afford abundant evidence of having been formed from the material of coral-reefs. Now corals and other reef-building organisms originally consist of aragonite, which appears under ordinary conditions to be less stable than calcite, and therefore more easily undergoes the change to dolomite. It is noticeable also that where dolomitisation is only partial it is specially prone to occur along major joints and fissures, and this fact suggests that it is effected by the agency of percolating water.

All calcareous organisms contain a certain amount of magnesium carbonate, generally not more than 1 per cent. Since this magnesium carbonate is less soluble than calcium carbonate, it has been suggested that it may be concentrated by differential solution. But this explanation seems to be insufficient, and breaks down when tested numerically, since concentration of the magnesium carbonate to only 10 per cent. would entail solution of 90 per cent. of the original rock.

The experimental work of Klement has shown that at temperatures above 60° C. aragonite is decomposed by magnesium sulphate in a saturated solution of common salt : the resulting product is a mechanical mixture of calcite and magnesite, containing as much as 42 per cent. of the latter mineral. This is not dolomite, but it is suggested that true dolomite may be formed as a result of subsequent changes. In nature a sufficiently high temperature may be found in the lagoons of coral atolls to produce conditions analogous to those under which Klement's experiments were made, and it is probable that the same process occurs, though at a much slower rate, at ordinary temperatures. Professor Skeats, in his researches on the dolomite rocks of the Tirol, has shown [1] that the process of dolomitisation is most effective in water from 0-150 feet in depth, which corresponds to a pressure of 1-5 atmospheres, and it is now believed to be due to a chemical interchange between the calcium carbonate of the rock, especially the aragonite organisms, and the magnesium salts of sea-water in these circumstances.

Besides the examples above mentioned, dolomite rocks occur on several horizons among the British strata : the best known is the Magnesian Limestone of Permian age, but other examples occur in parts of the Durness Limestone and the Devonian and Carboniferous Limestones of many localities.

Ironstones.—Iron is one of the most widely distributed of all metals throughout the visible portion of the globe, and rocks containing a notable proportion of this metal in the form of various compounds occur in innumerable localities. These rocks are of special interest, owing to their great commercial importance. They have been formed in several different ways, some having been deposited very much in their present form, while others are evidently due to alteration of rocks originally of different composition. Some masses of ironstone are directly due to igneous activity, and this class will not be further described here (see p. 275). The majority, however, are obviously of sedimentary origin, and many of them are closely connected with the calcareous rocks.

The process by which limestones are converted into ironstones belongs to the class of changes which come under the somewhat vague heading of *metasomatism* (see p. 271). All natural waters contain

[1] *Q.J.G.S.*, 1905, p. 97.

a certain proportion of iron compounds in solution, and these compounds react chemically with the calcium carbonate of the limestones. The calcium is driven out from the somewhat unstable lime carbonates, and is replaced by iron; this process appears to be a molecular one, so that the rock comes to consist of chalybite (ferrous carbonate) instead of calcite or aragonite, without, however, losing its characteristic minute structure. Hence many ironstones show very perfectly the types of structure which have already been described in limestones, and notably the oolitic structure. However, like all the ferrous compounds, chalybite is unstable and easily undergoes further changes, brought about by water containing gases and various soluble substances. The most important of these further changes are oxidation and hydration, so that the carbonate is replaced by the various hydrated and anhydrous oxides of iron, according to circumstances. The most important of these alteration products are limonite, $Fe_2O_3 + xH_2O$; hæmatite, Fe_2O_3; and more rarely magnetite, Fe_3O_4. In oolitic ironstones it is frequently observed that the oolitic grains are in a different state of alteration to the ground-mass, and this is probably owing in some measure to the fact that the limestone originally contained both calcite and aragonite, of which the latter is the less stable. As a rule the alteration has proceeded farther in the oolitic grains than in the matrix, so that we may have grains of limonite or magnetite in a matrix of chalybite or even calcite. One of the most important beds of ironstone, the Cleveland Main Seam in the Middle Lias of N.E. Yorkshire, shows various stages in this process; the iron ores of Northampton, Rutland and Lincoln are mostly limonite; while a thick mass at Rosedale, in the Cleveland Hills, is magnetite. Some limestones without the oolitic structure have also undergone a similar alteration, so that the rock now consists of a crystalline mosaic of chalybite, and the fossils are often perfectly preserved; in some rocks, originally calcareous grits, the calcite cement has undergone the same alteration, thus producing a ferruginous grit.

In the Coal-measures, and in other strata of similar character, there occur beds of ironstone, often somewhat impure from admixture of earthy matter. These are variously known as *Black-band ironstone* and *Clay ironstone.* The iron usually exists in the form of carbonate; some of these may have been deposited very much in their present state, while others are due to metasomatism of more or less impure limestones. It is probable that some of the black-band ironstones are of essentially the same origin as the bog-iron-ore presently to be described.

It is clear that in many cases the separation of the iron from solutions is due, either directly or indirectly, to the action of vegetable matter, especially when in a state of decomposition. The action is a complex one, but the final result is the precipitation of hydrated oxides of iron, usually limonite. This process goes on in lakes and marshes, and gives rise to *Lake-ore* and *Bog-iron-ore.* The former is very largely developed in the shallow parts of some of the Swedish lakes. Of essentially the same character is the so-called Moor-band-pan, a hard layer often found in boggy ground between the soil and the subsoil. These processes may possibly be due to bacteria.

Salt-deposits.—In certain parts of the world there are found deposits of salts which are freely soluble in water under ordinary conditions, and it is evident that special circumstances have led to their deposition and subsequent preservation. The chemical constituents ot these salt-deposits are those which occur in the waters of the sea and salt lakes, and they have evidently originated by the evaporation of salt water which has by some means become isolated. Some of these deposits are of great thickness, amounting to several thousand feet; since sea-water only contains about 3 per cent. of dissolved salts, they must represent the residue of an enormous volume of water. It is evident that the volume required could not be supplied by a simple closed basin, and the process can only take place on a sufficiently large scale in a locality where a supply of water is kept up to make good the loss, so that a constant volume is maintained and great concentration occurs. These conditions are very perfectly realised by the Kara Boghaz, an indentation on the eastern shore of the Caspian Sea. The strait connecting this basin with the sea is only a few hundred yards wide and very shallow, while there is strong evaporation and little or no access of fresh water, both of which are also essential factors. A strong current, running at several knots an hour, flows in to supply the loss by evaporation, and the strait is too shallow to permit of a return current at a lower level. Consequently the water of the gulf is a strongly concentrated solution, and the bottom is covered with a thick bed of rock-salt.

When normal sea-water is being concentrated by evaporation, gypsum begins to precipitate when 37 per cent. of the water has been evaporated, whilst when 93 per cent. of the water has been removed it becomes saturated for rock-salt. To bring down the still more soluble potassium and magnesium salts 98 per cent. of the water must be removed. In very many cases desiccation appears to have been incomplete, and either gypsum only, or gypsum and rock-salt, are found. This is the case in Britain, where salt-deposits are found in the Trias of Cheshire and Worcestershire, at Middlesbrough, and at Carrickfergus, near Belfast. Beds of gypsum only are still more widespread. The beds of rock-salt at Sperenberg, near Berlin, are 4,000 feet thick, and those of Wieliczka, in Austrian Poland, are nearly as thick. The latter are of Tertiary age.

The most interesting case of apparently complete desiccation is afforded by the Permian salt-beds of Stassfurt, in Central Germany, where in addition to the usual rock-salt and gypsum there are also numerous compounds of potassium and magnesium, often in the form of complex double sulphates and chlorides. A very elaborate experimental investigation by Van't Hoff and his pupils has established the order in which the different salts ought to crystallise out from mixed solutions containing the constituents of sea-water, and on the whole the arrangement of the Stassfurt salts agrees with their results.

The most important of the salts found are the following: Epsomite, $MgSO_4 . 7 H_2O$; Carnallite, $KCl . MgCl_2 . 6 H_2O$; Kieserite, $MgSO_4 . H_2O$; Polyhalite, $2 CaSO_4 . MgSO_4 . K_2SO_4 . 2 H_2O$; Leonite, $MgSO_4 . K_2SO_4 . 4 H_2O$; Kainite, $MgSO_4 . KCl . 3 H_2O$; Sylvite, KCl; and the iodides and bromides of potassium and other bases. Boracite also occurs.

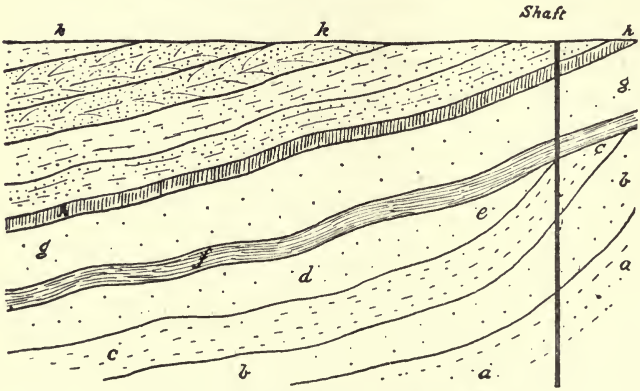


Fig. 59.—The Stassfurt Deposits.

a, Rock-salt; *b*, Polyhalite region; *c*, Kieserite region; *d*, Carnallite region; *e*, Kainite region; *f*, Impervious clay; *g*, Anhydrite; *h*, Gypsum; *k*, Sandstone.

Fig. 59 shows a diagrammatic section of the principal deposit. The lowest bed reached consists of rock-salt with layers of anhydrite, $CaSO_4$. In the upper part this is mixed with kieserite and kainite, and then comes a layer of carnallite. This is covered, with apparent unconformity, by a layer of impervious clay followed by a great thickness of anhydrite and gypsum. Above this are the sandstones of the Trias. The preservation of these highly soluble salts is due to the layer of clay above them, which protects them from percolating water. These salt beds are of very great commercial importance, and they are now the principal source of potassium and magnesium compounds, and also of iodine and bromine. The latter are obtained as by-products in the purification of the other salts.

Nitrates.—Deposits of nitrates are not abundant, and indeed can only occur under exceptional conditions, owing to their high degree of solubility. Potassium nitrate is found as an incrustation on the soil in certain dry districts in India and elsewhere. It is deposited by evaporation of saline solutions brought to the surface by capillarity. On a much larger scale are the beds of nitrate of soda mixed with other salts which are found in the rainless district of Peru, in the desert of Atacama, and these are of great commercial importance. The deposits of crude nitrate, called Caliche, are found up to a height of 5,000 feet above sea-level, and as much as forty-five miles inland. The nitrate of soda is associated with sulphates, chlorides and iodides, of potassium, sodium, magnesium and calcium, and also salts of boric acid. Two explanations of their origin have been widely put forward. According to one theory, they are weathered masses of animal bodies and excrement like the guano of Peru. Against this idea are the facts that they contain no phosphoric acid, and much iodine is present. The other theory traces their origin to masses of sea-weed, stranded by emergence of the land, and decomposed, giving rise first to ammonia compounds, and these, when acted on by bacteria, form nitric acid ; this forms calcium nitrate, which in its turn interacts with sodium sulphate, yielding sodium nitrate and gypsum.

Siliceous Sinter.—In certain regions of expiring volcanic activity there exist hot springs whose waters are rich in dissolved silica, and these give rise to large deposits of the material which is known as siliceous sinter. The conditions governing the stability of a solution of silica are imperfectly known, but it appears that the separation of silica in the solid form from hot springs is due to several causes, viz. relief of pressure, cooling, chemical reaction, evaporation and plant life. The first four tend to produce a supersaturated solution, and thus to cause separation of solid silica. But certain algæ, which live in hot water, are able to extract silica from solutions which are by no means saturated, and to deposit it in their tissues in the solid form. This gives rise to a layer of jelly-like material on the surface of the surrounding rocks, and when the plant dies the jelly solidifies to a porous or compact stony mass, either white or coloured by various metallic oxides.[1] The best-known deposits of siliceous sinter are those surrounding the geysers and hot springs of Iceland, the Yellowstone Park and New Zealand. They often assume very striking and beautiful forms, as in the case of the celebrated Pink and White Terraces of New Zealand, destroyed by the eruption of Tarawera in 1886.

Chert and Flint.—Many limestones of various ages have undergone more or less completely a process of *silicification*, in which the calcium carbonate has been replaced by silica in the chalcedonic form. The

[1] W. H. Weed, *Ninth Annual Report, U.S. Geol. Surv.*, 1889, p. 619.

change appears to have been in most cases a molecular one, since the minute structures of the rock are often very perfectly preserved. Such a rock is called a *chert*. Excellent examples of this process are found in the Upper Jurassic rocks of the Isle of Portland. In both the Lower and Upper Greensands of the south of England there are found beds a few inches thick almost wholly composed of chalcedonic silica, and associated with these are other beds rich in remains of sponges, originally siliceous, which have either been replaced by calcite or glauconite, or are represented by empty moulds. It appears that the silica of the sponge spicules has been dissolved away and redeposited as chalcedony in particular strata. Very similar cherts also occur in the Lower Carboniferous rocks of West Yorkshire and Ireland also associated with sponge spicules.

The Chalk of Southern and Eastern England contains many nodular and shapeless masses of black or grey chalcedonic silica, which are called *flint*. The origin of these has long been a matter of dispute, but it seems probable that they were formed in a manner essentially the same as that described above in the case of chert. Flints usually occur in lines and bands along the bedding or joints of the chalk, and sometimes form thin layers continuous over a considerable distance. They often enclose fossils, especially sponges; when examined microscopically sponge spicules are seen to be abundant in them. Prof. Sollas' explanation of the origin of flint is as follows.[1] The sponge spicules in chalk consist of opal, $SiO_2 + {}_n H_2O$, which is much more soluble than crystalline silica. It is either replaced by calcite or dissolved away completely, leaving hollow cavities. This dissolved silica is again deposited around siliceous patches in the chalk, in the chalcedonic form. Thus the formation of flints is to be ascribed to a form of concretionary action. It is not known when the process occurred, but it appears to be at any rate posterior to the jointing of the chalk.

Siliceous Oozes.—Reference has already been made to the radiolarian and diatom oozes which are at present being formed on the floor of the ocean far from land, and it was shown that deposits largely composed of radiolaria are specially characteristic of great depths. It is an interesting question to what extent similar deposits can be traced among the older rocks; and so far as is at present known they are rare. Cherts largely made up of the tests of radiolaria have been described from the Lower Carboniferous rocks of North Devon, and from Mullion Island off the coast of Cornwall, also from the Arenig rocks of the southern uplands of Scotland. These are fine-grained flinty-looking rocks commonly spoken of as radiolarian cherts. Their true nature cannot be regarded as established beyond all doubt owing to the bad

[1] Sollas, *Age of the Earth*, p. 133.

preservation of the organisms. The best-established case of deep-sea siliceous deposits of this kind is in the island of Barbados, where there are to be seen, at a height of 800 or 900 feet above sea-level, thick beds of siliceous rocks largely composed of radiolaria, and in association with strata which closely resemble modern abysmal red clays. There have also been found in this series remains of echinoids of deep-water type. Beds of very similar character are also found in Trinidad and other West Indian islands. It is concluded that this region must have undergone an elevation of many thousands of feet in comparatively recent times, probably since the Pliocene.

Phosphatic Deposits.—The natural compounds of phosphorus are of great commercial importance, chiefly in view of their value in agriculture. The mineral apatite, which consists chiefly of calcium phosphate together with calcium chloride or fluoride, is found in some parts of the world to a considerable extent, especially in Norway and Canada. This mineral, however, chiefly occurs in the igneous and metamorphic rocks, and cannot be further described here. However, phosphatic accumulations of sedimentary origin are also widespread, and of great importance, both scientific and commercial.

Phosphorus is an important constituent of living animal tissue, and most phosphatic deposits can be traced directly or indirectly to this source. In certain rainless districts, especially on the west coast of South America and S.W. Africa, there are found immense deposits of *guano*, which is composed almost entirely of the excrement and remains of sea-birds. It consists to a very large extent of nitrogenous and phosphatic substances, and is a most valuable manure.

In some cases beds of guano have caused a remarkable alteration of the underlying rocks. A good instance of this occurs in Christmas Island in the Indian Ocean, where some of the raised reef-limestones have been more or less completely converted into calcium phosphate. Another interesting case is that of Clipperton Atoll in the eastern Pacific, where a trachyte has been phosphatised to a varying extent in different parts of the mass, so that although the typical trachyte structure is still discernible, 95 per cent. of the rock consists of phosphates of lime and alumina. In this case it is supposed that ammonium phosphate derived from guano has replaced the silica and alkalies of the felspar. The phosphorite or Redondite of Redonda, in the West Indies, similarly shows the structure of an andesite, but consists of phosphates of iron and alumina.

In many sedimentary deposits, and especially in those of shallow-water origin, there are found nodular masses of phosphate of lime. Many of these are obviously the fossilised excreta of animals, while others are recognisable fossils, and others again are mere lumps of calcareous mud which have been changed into phosphate. Such phosphatic nodules are commonly and commercially known as *coprolites*, though strictly speaking this term should be confined to fossilised excreta. One of the best-known examples is the so-called Cambridge Greensand (for further description of this see Chap. XXVI). Such phosphatic nodule-beds are specially characteristic of what is known as pene-contemporaneous erosion, where strata have been removed by wave-action and currents soon after formation. The presence of the phosphate is probably accounted for by the abundance of life in shallow waters. In the modern seas, deposits containing phosphates and glauconite are now being formed in certain localities, very similar to the Greensands of the cretaceous. Some modern deep-sea deposits also strongly resemble the phosphatic chalk of the south of England, France and Belgium. In most of these cases it appears that phosphorus compounds of organic origin have reacted with calcium carbonate to form calcium phosphate. This process of phosphatisation may be reckoned among the metasomatic changes undergone by calcareous rocks.[1]

Carbonaceous Rocks.—Under this heading are included all those ancient and modern sedimentary deposits in which the most important constituent is carbon (rocks consisting chiefly of carbonates are excluded). From the practical and commercial point of view some of these are about the most important of all the known constituents of the earth's crust. As a matter of convenience, there are described here also certain carbonaceous substances found within the earth's crust which are certainly not rocks in the ordinary sense of the term, and are not even solid. Such are rock-oil (petroleum) and natural gas. These, however, closely resemble some of the carbonaceous rocks in chemical composition, and are naturally classed with them.

At almost all geological periods there have been formed in some parts of the world great accumulations of vegetable matter, which have frequently undergone a peculiar kind of decomposition, eventually forming substances of a more or less bituminous nature. The most important of these products is coal. Although the origin of coal is still a somewhat disputed question, it is universally recognised that it consists of remains of plants, and the question can be best approached by a study of modern analogies.

Peat.—At the present time there are found in many parts of the world great deposits of more or less decomposed vegetable matter of varying character, to which the general term of peat is commonly applied. The greatest developments of peat are seen in temperate and cold regions, where the climatic conditions seem to be most favourable

[1] A summary of the Phosphatic Deposits of the different geological systems, by Teall, is to be found in the *Proceedings of the Geologists' Association*, vol. xvi., 1899–1900, p. 369.

to its formation. It is rare in the tropics, while the greatest peat-bogs of the world occur in the arctic portions of Asia and North America, the Tundras, where the subsoil is permanently frozen throughout the year and the surface vegetation consists chiefly of mosses. Peat occurs to a considerable extent in the British Isles, and here it is possible to recognise two distinct types of slightly different composition—Hill-peat and Fen-peat.

Hill-peat consists very largely of the remains of *Sphagnum* and other mosses, and is usually a brownish or nearly black fibrous, spongy substance in which the vegetable structure is still clearly visible. It often encloses numerous trunks and branches of trees, such as the well-known bog oak of Ireland. It is usually found at fairly high elevations, especially in the widely spreading moors of the north of England and Scotland, but in the west of Scotland and in Ireland it is also seen at lower levels.

Fen-peat is commonly a darker-coloured and more muddy deposit, consisting largely of the remains of rushes, sedges and other water-plants. It is found at low elevations, such as the Fenland of Eastern England and the so-called 'moors' of Somerset (Sedgemoor, &c.). Here also buried forests are common, and frequently occur at definite levels, probably indicating variations of climate or periods of more effective drainage. Near Ely five such forests have been traced, and a similar succession is known among the peat-bogs of Denmark.

The depth to which peat has accumulated in British peat-bogs is very variable: it rarely exceeds 50 feet, and is usually much less. Of late years much attention has been paid to the character of the plants composing the peat, and it has been found that the constituents of the lower layers of many of the Scotch and English peat-bogs indicate that they were formed during the later stages of the Glacial period, and a definite succession can frequently be made out.[1] The growth of peat is evidently a very slow process, and in many localities appears to be almost stationary at the present time. The process of its formation is evidently a peculiar limited decomposition of vegetable matter while saturated by water, so that oxidation is in abeyance, and it is probably brought about largely by bacteria.

Lignite or *Brown-coal.*—This substance may be regarded as intermediate between peat and true coal. It is more solidified than peat, but still shows distinct woody structure. It differs from true coal in being of lower specific gravity, lighter in colour and less hard. Lignite is rare in Britain, the only important locality being in an Eocene lake-basin at Bovey Tracy in Devonshire, where it is interstratified with beds of china-clay. It is, however, common in the Tertiary

[1] Lewis, *Proc. Roy. Soc. Edin.*, 1907.

formations of the Continent, especially in Germany, where it forms an important source of fuel.

Coal.—The term coal, as commonly employed, includes several grades of fuel, which are used for somewhat different purposes. The names generally in use for these are: House Coal or Bituminous Coal, Cannel Coal, Steam Coal and Anthracite. It is not possible, however, to lay down any strict definition of each group. All the true coals are black in colour, either lustrous or dull, and show little or no trace of the original vegetable structure.

Bituminous coal is the variety used for domestic purposes, and is too well known to require description. It burns with a bright, very smoky flame. Cannel coal is a compact dull variety, which burns with a bright flame, and is used for the manufacture of gas. Jet is a hard variety of cannel coal, capable of taking a high polish. It is chiefly found in the Lias of Yorkshire. The terms steam-coal and anthracite are used somewhat vaguely, and sometimes interchangeably, to indicate hard varieties of coal, often with a semi-metallic lustre, which can be handled without soiling the fingers. They burn with a feebly luminous and smokeless flame, and for this reason they are of special value for war-ships. Steam coals and anthracites are chiefly worked in South Wales and in Pennsylvania.[1]

Chemical Composition of Coal.—All the carbonaceous rocks above mentioned, peat, lignite and all the varieties of coal, have the same qualitative composition, and differ only in the proportions in which the constituents are present. They consist of carbon, hydrogen, oxygen and nitrogen, together with a varying proportion of mineral matter which is known as ash. It has been generally assumed that peat, lignite, bituminous coal and steam coal form a series of progressive alternation—a decrease of oxygen and nitrogen, with a corresponding concentration of carbon and hydrogen. On this assumption the amount of ash ought to show a corresponding increase in the higher members of the series, since ash is non-volatile. Broadly speaking, this generalisation holds in the case of peat, lignite and bituminous coal, but in cannel coal and anthracite there is less ash than in bituminous coal. It is evident, therefore, that cannel coal and anthracite have originated in a somewhat different manner, although the exact nature of the difference is still somewhat uncertain. It is now generally believed that all varieties of coal have undergone a special kind of decomposition, probably due to bacteria, before they were covered up by the succeeding strata, and that the differences between bituminous coal, cannel coal and anthracite are original in this respect, that the vegetable slime, or *sapropil*, of which they were originally composed,

[1] For a full account of the character of the different varieties of coal, reference may be made to Dr. Walcot Gibson's *Geology of Coal and Coal-Mining*, 1908, and E. A. N. Arber, *The Natural History of Coal*, 1911.

was formed in each case under slightly different conditions or by different species of bacteria. Besides these original differences of composition, it appears to be certain that in some cases bituminous coal has been converted into anthracite by subsequent changes of the nature of metamorphism, but the nature of the agent which produced the change is still unknown.[1] It is clear that in the South Wales coal-field the degree of anthracitisation increases with the depth from the surface, and is also progressive from east to west; and it is noteworthy that the intensity of the disturbances to which the strata have been subjected also increases in this direction.

Origin of Coal.—It is obvious that the great accumulations of vegetable matter which gave rise to the coal-seams of the Carboniferous and other formations must have been laid down under peculiar conditions, and this subject has given rise to a good deal of controversy Two principal theories have been put forward in explanation: the *growth-in-place theory*, and the *drift* theory.

The former theory supposes that the plants which formed the coal originally grew in the position in which the coal is now found; the supporters of this theory rely on the purity of many seams and the frequent occurrence of a bed of fire-clay beneath the seam. This is supposed to represent the soil in which the plants grew. Roots of plants can often be seen in the fire-clay, while the stems pass through the seam up into the overlying rock. Where there is a rapid alternation of beds of coal and sandstone, for example, a rapid oscillation of the relative levels of sea and land is implied, and this is somewhat difficult to credit. A microscopic examination of certain seams, for example the Better Bed Coal of Yorkshire, has shown that the coal consists to a very large extent of the spores of lycopods. Now the spores of modern lycopods are very resinous, and will not sink in water, so that a coal composed of them must of necessity have been formed on a land-surface. The so-called Tasmanite, or White Coal of Tasmania, is a lignite of comparatively recent date having a similar structure.[2] The supporters of the drift theory point out that coal behaves exactly as a sedimentary rock, and coal-seams often pass laterally into beds of shale, clay, sandstone, or even dolomite rock. Coal-seams were thus formed during intermittent downward earth-movements, during the formation of a depression which became consecutively filled with coarse material (sandstone), followed by finer sediment (shale and clay), and finally by drifted plant débris, forming the coal.[3] In the case of the

[1] See 'The Coals of South Wales,' *Mem. Geol. Survey*, 1908, pp. 63–73.

[2] Newton, *Geol. Mag.*, 1875, p. 337.

[3] The substance of the foregoing paragraph follows closely Dr. Walcot Gibson's *Coal in Great Britain*. For further details reference may be made to chapter .ii. of that work. London: Edward Arn ld. 192?

coal-basins of Commentry, in Central France, a special mode of origin has been suggested. These basins lie on a plateau of Archæan rocks, with a very irregular surface. Evidently they were once lakes, into which vegetable matter from surrounding hills was washed by floods; they are now filled with a tumultuous accumulation of tree-trunks, &c., converted into coal.

Petroleum.—Only the fringes of the subject of petroleum and oil-geology can be touched on here, and those wishing to study the question in detail are referred to the works quoted below.[1] In many parts of the world the sedimentary strata are characterised by containing vast quantities of free hydrocarbons in the solid, liquid, or gaseous state, of which petroleum, the liquid form, is by far the most important economically. Under this term is comprised a varied and complex series of liquid hydrocarbons mainly of the paraffin series. Petroleum of very similar composition is also obtained by the destructive distillation of the bituminous or 'oil' shales found in certain areas. Closely allied to, and often associated with, petroleum are the gaseous hydrocarbons or 'natural' gas, consisting mainly of the lowest members of the paraffin series. The solid hydrocarbons vary considerably in type: pitch and asphalt are terms somewhat loosely used to describe the impure oxidised semi-solid residue resulting from the natural evaporation of certain types of oil. Distinct from these are the natural bitumens that occur as intrusive veins in non-bituminous strata. Those originating from asphaltic oils are usually black glistening bodies with fractures and properties that depend on their composition, and a natural light-coloured wax derived from oils rich in solid paraffins is known as ozokerite, and is similarly found in veins and slip planes.

Distribution.—Petroleum and allied substances are very widely distributed both stratigraphically and geographically; from the Devonian upwards most of the geological systems have indications of oil in some part of the world, although, with the exception of the Upper Palæozoic oil-fields of North America, the Tertiary formations are by far the most important as oil-producers. Geographically the distribution is just as wide, and practically no country is without some trace of oil, though many may not prove capable of economic development. Of those regions which have provided the bulk of the world's oil-supply in the past, the most famous are Pennsylvania, California, Oklahoma, and Texas in the U.S.A., Mexico, Russia (Baku and Grosny), Roumania, Galicia, Burma, and the East Indies. In Great Britain oil has for long been known to exist here and there in the Carboniferous, and in 1913 a boring put down for coal at Kelham struck a thin oil-sand. Recently several test wells have been commenced in Derbyshire and elsewhere, and at Hardstoft oil was struck in the Carboniferous Limestone at a

[1] A. Beeby Thompson, *Oil-Field Development*, 1916; E. H. Cunningham-Craig, *Oil-Finding*, 1920; Sir Boverton Redwood, *A Treatise on Petroleum*, 1913.

depth of about 3,000 feet, and the well had yielded up to May, 1920, about 3,000 barrels.

Oil shales are also of wide occurrence; they are found in the Lower Carboniferous of Scotland, the Jurassic shales of Kimmeridge and Norfolk; they are also found in Canada, U.S.A., Spain, and Australia. It is only in Scotland, however, that so far they have been successfully developed. Natural gas, though usually closely associated with petroleum, may sometimes occur alone. The U.S.A. provide many examples of wells giving huge quantities of gas only, while in this country it is often met with in the Coal Measures, and near Heathfield Station in Sussex a boring for water in the Wealden beds in 1896 tapped a supply of gas which continued for many years.

Asphalts and bitumens generally occur closely associated with oil, and one of the most remarkable occurrences of asphalt in the world is in Trinidad, where it forms a lake half a mile in diameter.

Origin of Petroleum.—The true source of petroleum is undoubtedly to be found in the decomposition and alteration of accumulations of organic matter, both animal and vegetable, and on the whole the evidence seems to point to animal remains being the more important. In small quantities petroleum has also been formed by the natural distillation of oil shales by igneous intrusions. The inorganic origin advanced by Mendeléef and others is now generally discredited.

Mode of Occurrence.—Oil is found saturating many types of rock, shales, sandstones, and limestones. In some cases oil has undoubtedly been formed in the beds where it occurs, but, being a liquid and subject to hydrostatic laws, it tends to ‘ migrate ’ and accumulate in the more porous rocks, especially if these are over- and under-lain by impervious strata. If these porous beds were already charged with water, the oil, being of lower specific gravity, will rise into the anticlines, the actual crest often being occupied by gas. In such circumstances the oil may be under high hydrostatic or gas pressure, giving rise to gushing wells of varying intensity when the covering strata are pierced. Where oil-bearing beds outcrop at the surface, or where, owing to a fault, dyke, or other circumstance, there is communication between the surface and lower beds containing oil under pressure, its presence may be revealed by ‘ seepages ’ or natural oil springs, mud volcanoes, gas issues, or asphalt deposits.

Concretions.—In many rocks of all classes there are to be found masses differing from the rest in composition or structure, or both, and possessing quite definite, though often very variable, forms. Many, though not all, of these have formed in the position where they now lie, either during or after the formation or the consolidation of the rock. For want of a better name these are all classed together under the general heading of concretions, though some of them have certainly not been formed by what are generally understood as concretionary processes. Such concretions are often more or less spherical in shape, also spheroidal or lenticular; sometimes nodular or botryoidal, or possessing many other forms. Some are scattered at random through the rock, while others are found only in more or less regular layers. Sometimes they lie so close in a particular stratum as to coalesce into a nearly continuous bed, and in such an instance they may be rectangular in form.

The nodular structures found in the igneous rocks are not of much importance or interest. Certain granites and diorites show a regular radial and concentric arrangement of their minerals, often with layers of dark and light minerals alternately, as seen in the orbicular granites of Scandinavia and the orbicular diorite of Corsica. This structure is due to rhythmic super-saturation and precipitation in a crystallising magma, as shown by Liesegang.[1] Some rhyolites and other lavas, again, show a nodular or lumpy structure probably produced during the change from a glassy to a crystalline condition (devitrification). The so-called 'orbicular weathering' of many igneous rocks is quite a different process, and the resulting rounded masses must not be confused with concretions: they are due to decomposition, not to growth.

The concretions of the sedimentary rocks are much more common and characteristic. They may occur in rocks of almost any kind, and are obviously formed in many different ways. Some are clearly formed during the deposition of the rock, while others are as certainly of secondary origin. There are also instances of doubtful relative age.

Perhaps the commonest of all concretions are the more or less spherical or ellipsoidal calcareous or ferruginous nodules which are so common in many clays and shales. In some parts of the country these are called *doggers*, especially when ferruginous. They are found in argillaceous rocks of almost all ages, and only a few examples can be mentioned; they are specially common in the Wenlock Shale, the Coal Measures, the Lias, and the Kimmeridge Clay. In the latter, as at Ely, they may be a yard across; from 6 inches to 1 foot is a very common size. The calcareous nodules of the Lias have been largely used for making Portland cement, while the ironstone nodules of the Coal Measures and of the Lias are in some cases valuable ores. When broken open they are often found to contain fossils, and frequently show what is called septarian structure, with a central cavity and more or less radial cracks, which taper outwards and do not reach the surface. These cracks often get filled up by calcite, iron carbonate, or even zinc-blende and galena. In certain cases, where a formation consists of an alternation of thin limestone bands separated by thicker layers of clay or shale, it has been suggested that the limestone bands may really be of concretionary nature, the calcium carbonate, at first spread almost uniformly throughout the rock, having been dissolved and reprecipitated along certain bedding planes, or the lime may have been brought in in

[1] Liesegang, *Die geologische Diffusionen*, 1913.

PLATE XXII

J. Romanes, photo.

(I) MORAINE BARRIER OF LOCH SKENE, MOFFATDALE.

J. Romanes, photo.

(II) GLACIATED ROCK BARRIER OF LOCH CORUISK, ISLE OF SKYE.

solution and rhythmically precipitated within the clay. In the case of the ironstone doggers, it is uncertain whether they were first formed as ironstone, or whether they were originally limestone concretions subsequently converted into ironstone; probably both cases have occurred. Very closely related to these calcareous and ferruginous concretions are the flints of the chalk, whose character and supposed origin is described on p. 152.

Some of the most striking concretionary forms known are those of the Magnesian Limestone in Durham, which have been well described by Professor Garwood.[1] These have most extraordinary shapes, such as botryoidal, reniform, dendroid, basket-like, and many forms which can only be described as fantastic, some closely imitating various organic structures such as sponges and corals. Professor Garwood shows that the concretions consist mainly of calcite, while the rest of the rock is highly dolomitic, and he concludes that they were formed by crystallisation of the original calcium carbonate of the limestone around fossils and other organic nuclei, some of which have since disappeared, leaving central hollows. Such concretions only seem to form in dolomitic strata, and are absent from beds in the same series which do not contain magnesia.

Many sandstones and ironstones contain structures commonly known as boxstones, which are in a certain sense the inverse of concretions, since the movement of the material seems to have been outwards, at any rate in part. Typical boxstones, such as are seen in the Lower Greensand, are spheroidal or, more commonly, more or less rectangular structures, generally hollow, sometimes empty, but usually containing loose, bleached sand. The walls consist of hard iron oxide cementing sand grains, and are often about half an inch thick. The original deposition of the iron is probably determined by joints, as it is very similar to the coatings of iron oxide so often found around natural joint-blocks of sandstone, as in the Carstone at Hunstanton and in many Jurassic sandstones in Yorkshire.

Another common type of concretion takes the form of radiate spherical or nodular masses of iron sulphide, generally marcasite, so often found in the Chalk. Many of the metallic and other minerals found in mineral veins and other ore deposits possess a concentric or radial structure, very like that of typical concretions, such as the well-known kidney-ore (hæmatite) and the very similar botryoidal masses of limonite and various manganese compounds, and the green concretionary lumps of bright green malachite found in the oxidised parts of copper lodes.

A puzzling type of structure is that known as cone-in-cone, where masses of calcite or other minerals of apparently concretionary origin are made up of numbers of conical or pyramidal pieces fitting one into the other and building up a continuous stratum. This structure is apparently due to a peculiar kind of crystallisation.

[1] *Geol. Mag.*, 1891, p. 433.

CHAPTER X

LAKES

It is a matter of considerable difficulty to frame a definition of a lake which will cover all possible cases, since their manner of origin shows very wide variations. Perhaps the simple statement that a lake is a hollow filled with water is the most satisfactory, although even in this the element of size has to be taken into consideration. The term lake is applied in ordinary language to a sheet of water of considerable extent, whereas the smaller bodies of water are distinguished as tarns, meres, pools and puddles. The term pond in this country is generally restricted to artificial structures, though in America this distinction is scarcely applicable.

The origin and character of several different kinds of lakes have already been dealt with, either incidentally or at length, in the preceding sections, and the present chapter is to be regarded merely as a summary. Detailed descriptions will be given only of types not before dealt with, and for the others reference will be made to the preceding pages.

Lakes can be broadly classified into three groups according to their manner of origin, as follows—

(1) Lakes due to the accumulation of a dam or barrier.

(2) Lakes due to erosion.

(3) Lakes due to differential earth-movement.

Besides these, there are also to be found a few types not included in any of the above classes, such as crater-lakes.

(1) **Barrier Lakes.**—From this class we exclude those cases in which the barrier is due to earth-movement, since this kind of barrier consists of the same material as the rest of the basin. The barriers in the sense here employed consist of transported material which has blocked up the course of a river or in some other way caused the formation of a basin-shaped hollow. The barrier may be either temporary or permanent. It must be noted, however, that these terms are only relative, since all lakes must eventually disappear either by draining or filling up. As a geological feature they are not long-lived, and in many districts silted-up lakes are a very common feature.

One of the commonest causes of a short-lived lake is the descent of an avalanche of snow or ice from a glacier across the course of a river. Behind this the water accumulates till it either overflows the dam or bursts through. In the latter case the destruction brought about in the valley below is often very widespread. Examples of this are not uncommon in mountain regions like the Alps or the Himalaya. Sometimes the rapid advance of the front of a glacier without any actual discontinuity may produce a somewhat similar effect, though of a somewhat more lasting character. In mountainous districts temporary lakes may also be formed by rock-falls and landslips, and even by mud-flows, as for instance between Visp and Zermatt. Of a slightly more lasting character are glacier-lakes in the strict sense, which have been fully dealt with in a previous chapter (see p. 102). Although their duration may be long as measured in years, they cannot be considered permanent in the geological sense, since they are liable to be altered by any disturbance of the glacier to which they owe their origin. A good example of this is afforded by the well-known Märjelen See, which empties itself more or less completely nearly every summer. It is obvious that only under special circumstances can such transitory and variable lakes show any definite shore-line or beach. Reference should here be made to the account of the Parallel Roads of Glenroy given on p. 103.

Many of the most important lakes of the British Isles and elsewhere are directly due to the formation of moraines and deposition of drift in river-valleys during the glaciation of the country, and indeed the connexion between glaciation and lake-formation is very close. All the larger sheets of water in the English Lake District, with the exception of Thirlmere, are believed to possess drift-barriers,[1] although it is a moot question to what extent erosion by the ice itself has played a part in excavating their basins. Some of them descend below the present sea-level, and it is difficult to avoid the conclusion that they are in part rock-basins, though the visible barrier in all cases consists of drift. We shall return to this question later. The origin of most of the smaller tarns of the Lake District,[2] North Wales [3] and the Highlands is also to be attributed to moraines, and in particular the small, more or less circular tarns which so commonly occur in cirques, cwms and corries are nearly always held up by a crescent-shaped moraine, probably formed when the cirque was filled by snow or ice during the Glacial period.

[1] Mill, *Geogr. Journ.*, vol. vi., 1895, pp. 46, 135 (published separately under the title *The English Lakes, Results of a Bathymetrical Survey*. London, 1895).

[2] Marr, *Q.J.G.S.*, 1895, p. 35, and 1896, p. 12; *Proc. Geol. Assoc.*, vol. xiv., 1896, p. 273.

[3] Jehu, *Transactions of the Royal Society of Edinburgh*, vol. xl., part ii., p. 419; Marr and Adie, *Geol. Mag.*, 1898, p. 51.

It is not uncommon for the lowest part of the course of a river in the immediate neighbourhood of its mouth to be converted into a lake by the accumulation of a high beach of shingle (storm-beach). By this means the stream is ponded back and an expanse of water is formed which may be either salt or fresh according to whether or not it is invaded by high tides. This subject trenches closely upon the province of beach accumulation and marine deposition (see p. 116) and need not here be further pursued in general terms. There is, however, in Britain one very important case, that of the Norfolk Broads.[1] In former times a river flowed through Norfolk with a wide estuary opening into the sea to the north of Yarmouth. Now the prevailing set of the tides and currents along this coast is from the north, and they bring with them much material from the destruction of the soft strata of Yorkshire and Lincolnshire. This material formed a spit, which eventually blocked up more or less completely the mouth of the river, and inside this barrier great sedimentation took place in a somewhat irregular manner, leaving areas of water and a complicated network of channels connecting them : these are now the characteristic features of this district. The silting up of the estuary has been assisted to a great extent by the luxuriant growth of rushes, sedges and other water-plants, which act partly by checking the movement of the suspended matter in the water and causing it to settle down, and partly by the decay of their own vegetable substance.

Somewhat analogous to the foregoing is a phenomenon which occasionally presents itself in regions where sand-dunes are a prominent feature. In the south-eastern angle of the Bay of Biscay, in the district known as the Landes, the advance of sand-hills is sometimes so rapid that the streams are unable to carry away the sand blown into them, and become choked. By this means lakes may be formed, but they are not of much importance.

In hilly regions, where the growth of peat is highly developed, it is not uncommon to find small tarns formed by its agency, and curiously enough these tarns are frequently situated on the cols between adjoining valleys. The reason for this peculiarity is not very clear, but it is probably connected with the outward growth of the peat in all directions from a centre. Sometimes where large expanses of peat exist at high elevations they may be much exposed to wind, and during dry periods much material may be blown away, forming hollows which afterwards become filled with water. The margins of these peat-formed lakes often show on a small scale an almost complete imitation of wave-cut coast-lines ; this is due to wind action.[2]

[1] J. W. Gregory, *Natural Science*, vol. i., 1892, p. 347.
[2] Rastall and Smith, *Geol. Mag.*, 1906, p. 406, with figure.

(2) **Lakes due to Erosion. Rock-basins.**—For many years past there has been much difference of opinion as to the possibility of the formation of lake-basins by glacial erosion, but it is now generally believed that this process has taken place on a considerable scale, and has led to the formation of lakes in regions formerly glaciated. This subject is discussed elsewhere (see p. 101). There is also another type of denudation which may give rise to somewhat similar results, viz. solution. As already pointed out, certain rocks, e.g. limestone, dolomite and beds of gypsum and rock-salt, are soluble, and their removal by this means may give rise to hollows, which become filled with water. It is believed that some of the lakes of the Alpine region, e.g. the Ticino valley,[1] have been formed in this way, since such comparatively soluble rocks here occur in patches intercalated with the less soluble ones, and the lakes often lie along the strike of beds of dolomite, gypsum, &c. Again, such beds existing underground, though not exposed at the surface, may be removed by solution, so that the overlying strata sink, thus forming hollows such as some of the meres of Cheshire.[2] This process may readily be mistaken for differential earth-movement of tectonic origin, and its true nature is difficult to prove. Analogous to this is a phenomenon sometimes seen in limestone regions, where the collapse of a cave with an underground river may give rise to a long, narrow, and possibly winding sheet of water, especially if the exit is blocked by the falling in of the roof[3] (see Fig. 60). The temporary or permanent blocking of a swallow-hole might have a similar result. In some of the great caves of limestone regions, underground lakes are a not uncommon feature.

(3) **Lakes due to Earth-Movement.**—This class is one of particular interest and importance, since it includes some of the largest detached bodies of water on the surface of the globe. In conformity with the special conditions which prevail, such lakes may be either salt or fresh. Excellent examples of the former kind are afforded by the Caspian Sea, the Sea of Aral and some smaller salt lakes in South-western Asia. The level of the water in the Caspian is now 84 feet below that of the Black Sea, while that of the Sea of Aral is 128 feet above the same datum line. It is believed that they were once continuous, since banks of shells of species now living in the Caspian extend widely over the area between it and the Sea of Aral. It is, however, doubtful whether they were connected with the Black Sea, since the seals of the Caspian show more affinity to *Phoca vitulina*, a northern form, than to *P. fœtida* of the Mediterranean: it is therefore inferred that a strait once existed connecting this region with the Arctic Ocean. It is not clear whether

[1] Garwood, *Q.J.G.S.*, vol. lxii., 1906, p. 165.

[2] Ward, *Geol. Mag.*, 1887, p. 517.

[3] Delabecque, *Les Lacs Français*, Figs. 49, 53, 104, and Plate VII.

the difference of level of the two chief remaining bodies of water is due to differential movement or to the settling down of the water into original inequalities in the bed. It is at any rate clear that the separation from the Arctic Ocean was due to an uplift on a large scale. The origin of the Dead Sea and of the great African lakes of the Rift valley is dealt with in the chapter on Earth Movements (see p. 181). The physical history of the great lakes of the St. Lawrence region in North

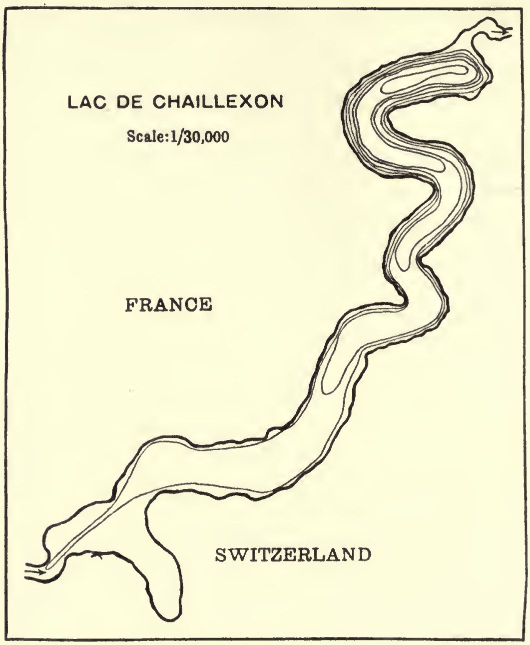


Fig. 60.—Sketch Map of Lake Chaillexon, France.

An example of a lake formed by the collapse of a cave with an underground river in a limestone district.

America has been dealt with by J. W. Spencer[1] and others. The question is somewhat complicated by glaciation, but according to Spencer crust-movements have here played an important part. Around most of the lakes are raised beaches, and these are now at different heights above sea-level in different parts, so that it appears that not only has the country been uplifted, but also tilted. The term employed by American writers to express this bending of the crust is *warping*.

[1] *Q.J.G.S.*, vol. xlvi., 1890, p. 523.

At one time there existed great lakes in the Great Basin region of North America. At the time of their maximum extension the climate was much moister than at present; conditions of aridity set in later, and still prevail. The shrunken relic of one of these bodies of water is the Great Salt Lake of Utah. The origin of these lakes is attributed by Russell[1] to the sinking and tilting of faulted blocks, i.e. basin-range structure (see p. 179). Lake Bonneville was about 300 miles long, and covered about 20,000 square miles in extent, and Lake Lahontan was nearly as large. Some of the phenomena displayed by the ancient beach-terraces of these lakes are described in a subsequent section.

Crater-lakes.—It is not unusual to find the craters of dormant or extinct volcanoes occupied by lakes, which naturally possess a more or less circular form. One of the best examples is afforded by the Maare of the Eifel district in Western Germany. These now consist of circular pools of water surrounded by a low ring of fragmental rock, which has been ejected by the volcanic outbursts. There is no lava, and the ejecta consist chiefly of fragments of the country rock, mostly Devonian slate. Each of these is believed to represent a vent of single explosion. In Central Italy there also exist several crater-lakes, such as Bolsena, Bracciano, &c., which lie in the craters of some of the long extinct volcanoes of that region. In the crater of the Soufrière in St. Vincent, before the eruption of 1902, there was a large pool of water containing abundance of sulphur compounds, which overflowed at an early stage of the eruption and caused a considerable amount of destruction.

Deposits formed in Lakes.—The nature of these depends to a great extent on the size of the lake. The larger sheets of fresh water, such as Lakes Superior, Michigan, &c., present characters very similar to those of the sea in many respects, and the deposits now being formed in them differ chiefly from those of marine origin in their organic contents. The lake-deposits found among the older stratified rocks are also of very similar character, but are readily identified by their fossils. When, however, we turn to salt-lakes, and those possessing no outlet, we find an assemblage of characteristic deposits, such as beds of rock-salt, gypsum and other substances, which throws light on the conditions under which the lake exists. Numerous instances of this occur in both ancient and modern times, but many of these are dealt with in detail in the chapter on the sedimentary rocks. In lakes in desert regions a large amount of fine material is frequently carried in by wind, and forms deposits of marl, &c., which are frequently interstratified with beds of salt and gypsum. In this way some of the Trias marls may have originated; the lakes of Central Asia are now being filled up by blown sand.

[1] *Sketch of the Geological History of Lake Lahontan*, p. 202.

At the mouths of rivers running into lakes conspicuous deltas are commonly formed, and in process of time the lake may become wholly filled up by this means. Not infrequently also there is a considerable accumulation of material near the outlet. In ordinary cases a lake is first converted into a swamp and then into level meadow-land. Such alluvial flats are common in many districts. Where a considerable stream runs in at one side of a lake, its delta may eventually increase in size so as to divide the lake into two, connected by a short length of river. This has happened in the case of Buttermere and Crummock Water, in Cumberland, and the large alluvial tract between Derwentwater and Bassenthwaite is of similar origin. These two lakes originally formed a sheet of water ten or eleven miles long, but it so happened that two important streams entered it nearly opposite one another, near Keswick—on the east the Greta or Glenderamackin, draining Thirlmere and the Troutbeck valley, and on the west the Newlands beck. Owing to the great amount of material brought down by these streams, the two lakes are now separated by about four miles of alluvial flat.

It is to be noted that the silting-up of lakes is in nearly all cases largely assisted by the growth of plants—peat at high elevations; rushes, sedges, &c., at lower levels. These act partly by straining off the suspended sediment, thus causing it to settle down, and partly by their own growth and decay, which gives rise to an accumulation of solid matter.

Topographic Forms of Lake-shores.—In large lakes the forms of the shore-lines present a great similarity to those of the sea, with certain differences. In the first place there are no tides, hence the beach tends to be much narrower and more sharply cut, since wave-action is limited to a very narrow zone. Again, the absence of appreciable currents causes less drift of material. In some lakes there occur slight periodic oscillations of level, called *seiches*. The origin of these is not thoroughly understood, and as they usually amount to a few inches at most, their geological effects are negligible. The formation of lake-beaches must be due almost entirely to wave-action during storms, and the process is perhaps more rapid than might have been expected. A few years ago Thirlmere was converted into a reservoir by the Manchester Corporation and the level was artificially raised, so that the original shore-line was submerged. However, in this short space of time distinct beaches of accumulation have been formed at the higher level.

Since the outlines of lakes are frequently very irregular, consisting of an alternation of points and bays, the accumulations of shingle, &c., forming the beach usually show a catenary curve, and this is often very marked. Sometimes a small rocky promontory, or what was once a small island, is connected to the shore by a double curve of beach, one on either side: this structure is called a *tombola*.

Vanished Lakes.—The existence of lakes which have now disappeared is attested in various ways. Besides the alluvial flats before described, beaches at various levels may sometimes be seen. The best example in this country is afforded by the Parallel Roads of Glenroy. These are due to a glacier lake (see p. 103). In the Great Basin region of Western America high-level lake-beaches exist on a very large scale, and the best example is in the district around the Great Salt Lake of Utah. This is a shrunken remnant of a once much larger sheet of water, and has now become intensely salt, owing to the loss of its

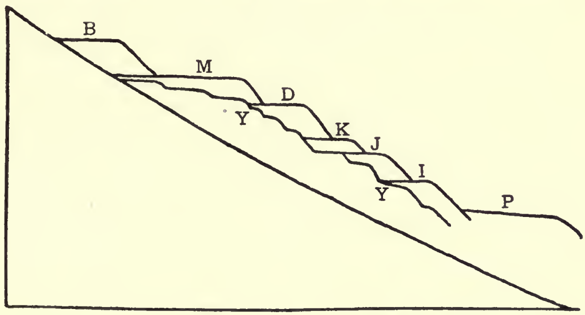


Fig. 61.—Diagram to show the Beaches of the Bonneville Basin. (After Gilbert.)

YY, Oldest beaches; *I to M*, Intermediate shore-lines; *B*, Bonneville shore-line; *P*, Provo beach.

The order of succession of the oldest series, *YY*, has not been determined. After the formation of the last of these, the lake is supposed to have dried up. Subsequently increase of rainfall gave rise to another lake, which formed the beaches *I* to *B*, in upward succession. After the formation of *B*, the level fell rapidly to *P*. The water remained some time at this level, forming a conspicuous beach. After this the fall seems to have been continuous, so that no further terraces were formed.

outlet. Around it, at heights up to 1,000 feet above its present level, are conspicuous terraces, marking the shore-lines of the former Lake Bonneville at different periods of its existence, when the climate was much moister than it is now, probably during the Glacial period or periods (see Fig. 61).

It has been shown by Gilbert[1] that the geological history of Lake Bonneville was a complex one, and two distinct periods of high-water can be distinguished, separated by an interval in which the lake seems to have dried up completely. Two principal beaches can be distinguished: the Bonneville beach, about 1,000 feet above the present level of the Great Salt Lake, and the Provo beach, some 400 feet lower;

[1] *Contributions to the History of Lake Bonneville.*

between these are a series of terraces of less importance. It is possible to determine the relative ages of these beaches (see Fig. 61), and it appears that most of them were formed while the lake was rising, as shown by their mutual relations. The Bonneville beach marks the maximum height of the water, and from this point the level fell rapidly some 400 feet, owing to the wearing away of the outlet. When the level of the Provo beach had been reached, the outlet was barred by an unusually resistant bed of limestone, so that the water remained constant at this height for some time : hence an unusually conspicuous beach was formed. It is possible that at this period the lake permanently lost its outlet, owing to increase of evaporation. The terraces just described rest on an older series, but it has not been found possible to make out the order of superposition of these, and it is not known whether they were formed during a rise or fall of the water. The highest of them marks a maximum only slightly below that of the Bonneville beach, and indicates the climax of the first wet period : the Bonneville beach marks the climax of the second. Thus a study of these ancient terraces yields some important and interesting information as to climatic vicissitudes in this part of the world.

CHAPTER XI

EARTH MOVEMENTS

THERE is abundant evidence that the crust of the Earth is structurally in a state of unstable equilibrium. As has been pointed out in the introductory chapter, strata originally horizontal are now found to be tilted, folded, faulted and otherwise disturbed; in fact, it is exceptional for this not to be the case. Besides this evidence of movement in the past, the occurrence of earthquakes and other observable disturbances at the present day shows that the same processes are still in operation. As a matter of convenience, crust movements may be considered under two headings—*rapid* and *slow*—although the difference between them is only one of degree, not of kind. Rapid movements are those which produce sudden and violent changes in a short period, while slow movements are usually only to be discerned by the effects produced after a long lapse of time.

Rapid Movements.—Observation by means of sensitive instruments has shown that the crust is in many parts of the world in a state of almost constant vibration, and that there exists every gradation between these minute tremors and the conspicuous disturbances which are called earthquakes. Even in our own country, which is commonly regarded as a very stable region, these tremors can be detected. In Perthshire, near the Grampian fault, they are of constant occurrence, and earth-shakes of measurable intensity often occur at the rate of two or three per day.[1] It is significant that this district is close to the great Grampian fault, which forms the southern boundary of the Highlands.

Earthquakes.—Tremors and sudden disturbances which are powerful enough to be sensible without the aid of instruments are popularly known as earthquakes. It is evident, however, that no hard and fast line can be drawn between these and the slight tremors described in the last section; the difference is one of degree only. Earthquakes can be conveniently divided into two classes: (1) those of volcanic

[1] Davison. *Geol. Mag.*, 1908, p. 296.

origin, and (2) those which are due to crust movements unaccompanied by vulcanicity. These two classes differ to a certain extent in character as well as in origin. Of late years the study of earthquakes has attracted much attention, and for full details reference must be made to the writings of Milne, Davison, Oldham, Dutton and others.[1] It is only possible in the space here available to give a short summary of the most recent views on the subject.

Earthquakes of Volcanic Origin.—The eruptions of volcanoes are generally accompanied by disturbances of the ground in their neighbourhood, and in volcanic districts shocks often occur unaccompanied by any eruption. These are in most cases undoubtedly due to the volcanic activity, and very often such a shock may be regarded as an unsuccessful attempt at an eruption. An excellent example of an earthquake of volcanic origin is afforded by that which destroyed the town of Casamicciola, in the island of Ischia, in 1883. Although the whole town was laid in ruins, and nearly 2,000 lives were lost, the shock was scarcely felt at Naples, only twenty miles distant. The smallness of the area of great destruction in this and similar cases is to be accounted for in two ways: partly by the slight depth at which such shocks originate, and partly by the smallness of the total energy involved.

Dislocation Earthquakes.—Of far greater importance than the foregoing class are the shocks which are due to actual movements of parts of the earth's crust. These are to be regarded as subsidiary phenomena accompanying the slow massive movements, which will be dealt with in a subsequent section. In fact, earthquakes form the most important part of the evidence for the occurrence of such movements at the present time. The shocks of this class are now considered to be due to sudden slipping of the walls of a dislocation, such as a fault or thrust plane. The walls of such dislocation planes are rough and the friction is great, so that when a slip does occur a sudden jar is communicated to the surrounding rocks. It appears that the actual amount of slipping needed to produce a considerable shock is very small, usually only a fraction of an inch. In some cases, however, relative displacements measurable by feet have been suddenly brought about during earthquake-shocks, as in Japan in 1891 and in Assam in 1897, where the visible relative displacements amounted to about 20 and 30 feet respectively. Earthquakes of this kind are specially notable, in contrast to volcanic quakes, for the great extent of country over which they can be felt. They are also always accompanied by what are known as

[1] Milne, *Earthquakes*, 4th ed., 1898. Davison, *A Study of Recent Earthquakes*, London, 1905. Oldham, *Q.J.G.S.*, lxii., 1906, p. 456. Dutton, *Earthquakes*, London, 1904. Hobbs, *Earthquakes. Beiträge zur Geophysik*, viii., Band 2, Heft 1906–7, p. 219.

after-shocks, a series of tremors of gradually decreasing intensity, which sometimes continue for days, weeks or even months. They are caused by the gradual settling down into a state of equilibrium of the disturbed blocks, and rarely or never occur after volcanic quakes. Minor earthquakes are also caused in certain regions by the falling in of caverns.

Nature of Earthquakes.—An earthquake may be defined as a series of vibrations set up in the rocks of the crust by an impulse, or series of impulses, originating at a greater or less depth below the surface. The exact nature of these vibrations or waves will be considered later in the light of recent results. The shock may originate at a point, or over a more or less extensive region; in volcanic quakes the origin is often very limited, approaching a point, but in dislocation quakes the origin is obviously in most cases a plane, which may be either vertical or inclined at any angle. From this origin, which is called the *focus*, the shock travels outwards in the form of waves, the surface of distribution being at any moment approximately a sphere, with the focus as a centre. Evidently, however, if the focus is linear the waves will not be spherical, but ellipsoidal. Such waves will obviously emerge on the surface as ellipses, and the intensity of the shock will vary inversely as the square of the distance from the focus, so that if we join on a map all the points at which the intensity is the same, we shall obtain a curve showing the form of the section of the wave-surface cut by the earth's surface. Such a curve is called an *iso-seismal line*; and diagrams of these lines have in many cases afforded important information about the relations of earthquakes to known tectonic features, and especially to faults, since the long axes of the ellipses are often found to be parallel to important lines of dislocation. On the other hand, when the long axis of such an ellipse is not parallel to any known dislocation, it is a fair inference that such exists below the surface, though concealed by overlying deposits. The intensity of the shock at any given point is also affected by other factors: as would naturally be expected, the waves are transmitted most freely by solid rocks, while their velocity is much reduced by loose material, such as sand, though the destructive effect is often very pronounced in regions covered by such deposits as alluvium and swamp soils.

Depth of Origin.—Many attempts have been made to determine the depth at which the shocks originate, but the methods hitherto employed are somewhat uncertain, owing to the doubtful accuracy of the data available. The oldest and simplest method depends on observations of the direction of cracks produced in buildings, on the assumption that these are at right angles to the direction of propagation of the waves. Lines are drawn at right angles to the cracks in buildings situated some distance apart, and the point of intersection of these perpendiculars is assumed to be the focus. This method gives fairly concordant results, usually ranging from five to twenty miles for the depth of the more important shocks. The results arrived at in other ways are in general accordance with this.

Earthquake Waves.—When a solid body is subjected to a sudden strain or shock, either of compression or torsion, vibrations are set up within it, which take the form of waves of various kinds. In solids two kinds of waves are possible : waves of compression and waves of distortion. In the former type, the particles move backwards and forwards in the direction of their transmission : these may be called longitudinal waves. In waves of distortion, the particles vibrate in directions transverse to the direction of transmission. By means of modern instruments of precision it has been found possible to analyse earthquake waves, and it is found that both kinds of waves are always present; besides these, a third kind of wave has recently been discovered, consisting of actual undulations of the superficial layers of the earth, of long period compared to the others. The nature of these surface waves is as yet hardly understood. The different kinds of vibrations travel at different rates, so that when a record of a very distant shock is obtained the traces of the waves of each kind are clearly separated. It is found that the longitudinal waves have an average velocity of about three miles per second, while that of the transverse waves is about half this amount. At a great distance also the former are much less intense, and make themselves manifest as the 'preliminary tremors' which herald the arrival of the main shock in all great earthquakes. The main shock seems to be due to the joint action of the transverse waves and those of the third kind, the surface waves, which are propagated along the outer crust and therefore travel along the circumference of the spheroid. Waves of the other kinds travel through the earth, but not quite in straight lines, since they are refracted at the bounding surfaces of masses of rock of varying density ; hence the velocities of the two kinds of waves are different, since they are unequally refracted and arrive at different points at different times.[1]

Geological Effects of Earthquakes.—Although the phenomena which accompany a great earthquake are such as to produce a great impression on the mind of man, their geological importance is usually considered to be but small. The actual changes brought about by them are generally quite insignificant, except in so far as they affect human handiwork. A very common accompaniment to important shocks is the formation of open cracks in the ground, especially in loose material, and from these cracks water, mud and sand are sometimes ejected : in mountainous regions important landslips often occur. In some cases there is good evidence of an actual change of level, with

[1] Oldham, *Q.J.G.S.*, lxii., 1906, p. 456.

differential movement. Reference may be made to the visible faults produced during the Mino-Owari earthquake in Japan in 1891, and the Assam earthquake of 1897. In New Zealand, in the year 1855, an area as large as Yorkshire was permanently elevated several feet, and in 1897 part of the land bordering Disenchantment Bay, Alaska, was raised 47 feet. The classical instance of such a displacement is that described by Darwin in Chile in 1835,[1] and there is good evidence to show that such a phenomenon has occurred again and again in that region, resulting in a total elevation of many hundreds of feet, since the advent of still-existing species of shells.

Simple and Twin Earthquakes.—A comprehensive study of many recent shocks in Britain and elsewhere by Dr. Davison[2] has shown that they belong to two distinct types: in simple earthquakes there is only one principal shock, which is clearly due to slipping along a fault-line of the ordinary type, such as is formed by simple vertical displacement; in other cases the shock is double, consisting of two principal shocks with a short interval of time between them: the origin of this latter kind is rather obscure.

Submarine Earthquakes.—A good many earthquakes appear to originate beneath the sea, and these chiefly manifest themselves by the waves to which they give rise: these waves often cause tremendous damage and loss of life on the coasts of the neighbouring land. Their origin is apparently to be sought in an uplift or subsidence of the sea floor. If the cause is a subsidence the sea retreats from the land before advancing, whereas in the case of an uplift the advancing wave is the first sign of disturbance. The great earthquake of Lisbon in 1755 seems to have been of submarine origin. It also appears that earthquakes may originate by the sliding of great masses of sediment down steep sub-oceanic slopes, such as frequently border the great continents. Such appears to be the cause of some of the earthquakes of the west coast of South America, and of some of those in the West Indies, e.g. Kingston, Jamaica.

Some recent Earthquakes.—Within recent times many disastrous earthquakes have been recorded, and the supposed causes of some of these have already been mentioned. Of these, the Japanese shock of 1891 and the Indian one of 1897 were clearly due to movements along lines of dislocation, which were indeed clearly visible on the surface of the ground: to the same class belong the well-known quakes of Charleston in 1886 and Andalusia in 1884. More recent examples are the San Francisco earthquake of 1906, where also there was a measurable displacement on the surface, and the terribly destructive shock which

[1] *Proc. Geological Society*, vol. ii., 1837, p. 446.

[2] *A Study of Recent Earthquakes*, London, 1905, p. 5.

destroyed the cities of Messina and Reggio on December 28, 1908. In the latter case the area specially affected lies close to one of the great lines of folding of the Alpine system, as will be explained in the course of this chapter, and moreover it lies on the inner or concave side of the curve, which is always specially liable to movements of subsidence. The Messina earthquake is obviously to be attributed to a settling down of the depressed area which now forms the Tyrrhenian Sea.

Slow Movements.—Although the rapid movements of the crust described in the preceding sections are the most obvious and striking in some of their effects, and indeed the only ones which are actually visible while in progress, yet they must be regarded as mere subsidiary incidents in a series of much greater phenomena. When a fracture is accompanied by relative displacement, it is only to be expected that this movement of displacement will occur intermittently, owing to friction between the rough fractured surfaces. These sudden slips give rise to earthquake shocks, and their sum-total, during the lapse of a long period of time, forms the greater movements which originate the leading structures of the visible part of the earth: these have led in innumerable cases to disturbances of extraordinary magnitude and complexity. From a detailed study of the effects of disturbances in many widely separated regions it has been found possible to discriminate between the different types, and to classify them under two principal headings, viz. *Continent-building* or *epeirogenic,* and *mountain-building* or *orogenic.* Broadly speaking, in the former class the movements are in a radial direction, while in the latter they are tangential.

Continent-building Movements.—This class includes the greater movements which have given rise to the broader features of the earth's surface, the continents and ocean-basins. These can in most cases be regarded as simple arches and troughs, or crust-waves of enormous amplitude. This is best exemplified in the case of the American continent and the Atlantic Ocean; here the boundary between sea and land is something of the nature of a simple monoclinal flexure. As will be shown later, the boundary of the Pacific is complicated by the interference of mountain-building movements, and the same applies in a greater or less degree to the other oceans.

At the present time it is a matter of dispute whether uplift can occur on a large scale: according to Suess and his followers actual uplift, or movement in a line away from the earth's centre, can only occur locally, as a result of lateral thrust, during mountain-building movements. The question is difficult or impossible to decide with certainty, since the only datum line we possess is the level of the sea, which is not necessarily constant. To avoid the assumption of a fixed sea-level, Suess speaks not of uplift and subsidence, but of positive and negative movements. Positive movements are those which are indicated by an apparent rise of the sea with regard to the land, while the reverse case is called negative. According to Suess, positive movements are caused either by an actual subsidence of blocks of the crust towards the centre, under the influence of gravity, or by a filling up of the ocean-basins by deposition of sediment causing the water to overflow. Negative movements, on the other hand, are caused by a subsidence of the sea floor in another area, thus drawing the water away from the land and lowering its actual level. Since we can only observe these movements in a relative sense it is convenient to speak of them as uplift and subsidence, without regard to their absolute direction as referred to the earth's centre: the only point of practical importance is as to whether the movement raises land above the sea-level, thus exposing it to denudation, or lowers it into the area of sedimentation.

The Permanence of Ocean-basins.—In the early days of stratigraphical geology it was assumed, especially by Lyell, that there had been a constant interchange of place between land and sea; that every alternation of marine and fresh-water sediment, and every phase of denudation and unconformity, implied a great change in the relative distribution of land and sea. Later arose a school which denied the possibility of such vast and comparatively rapid changes; and these went almost as far in the opposite direction, maintaining that the positions of the continents and oceans had been marked out once for all, from the beginning of the world, and were in their broader lines immutable. They insisted especially on the absence of true deep-sea deposits in the interior of the continents, and maintained the shallow-water character of the known marine sediments. Even now the stratigraphy of the central parts of the larger continents is imperfectly known; but when fully worked out it will probably be found that marine sediments are only well developed around the margins of the greater continents, or in depressed regions like the Mississippi basin. They are indeed abundant over a large part of Western Europe, but never far from the sea; and it must be remembered that Europe is a small division as compared with Asia, Africa or America, especially if we exclude Russia, which structurally for the most part belongs to Asia. Western Europe is, in fact, merely the seaboard of the great Eurasian continent. The prevailing idea at the present time is that the major divisions of land and sea have existed for a very long time, but that variations of level have caused alternate submergence and emergence of marginal regions, which happened to include those in which the stratigraphical sequence was first studied in detail, so that the general conclusions drawn were somewhat misleading. Arguments have also been brought forward based on the geographical distribution of animals, in which some zoologists have postulated the existence of great continents, especially in the southern hemisphere, in comparatively recent times, even so late as the Tertiary. In these ideas, however, most geologists are not disposed to concur.

Plateau-building Movements.—This name is applied to those vertical uplifts and subsidences on a smaller scale which diversify the surfaces of the continents: they may be described as producing minor platforms on the general surface of the continental masses, and are therefore to be regarded as a sub-class of epeirogenic movements. Structures of this kind are not largely developed in Britain, or, indeed, in Europe; to study them satisfactorily we must turn to Western America, where

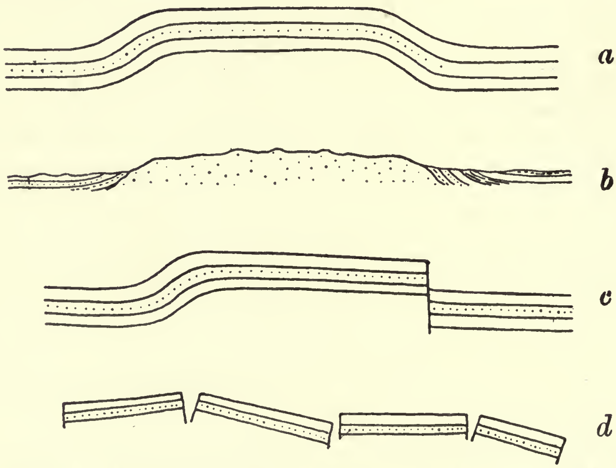


FIG. 62.—TYPES OF STRUCTURES PRODUCED BY PLATEAU-BUILDING MOVEMENTS. (After Powell, with slight modifications.)

a, Uinta structure; *b*, Park Plateau type; *c*, Kaibab structure; *d*, Basin-range structure.

they have been worked out in great detail by the members of the United States Geological Survey. In the great plateau region of Colorado and Utah the following types of structure have been recognised:—

(1) *Uinta Structure.*—This is well seen in the Uinta Mountains. It consists of two large monoclinal flexures, in opposite directions, each with the downthrow on the external side, leaving a broad elevated tableland between them (Fig. 62*a*). In the particular case referred to the flexure on one side passes over into a fault, with a throw of some thousands of feet.

(2) A special modification of this type is afforded by the *Park Plateau,* which constitutes the Yellowstone Park region, and appears to be connected with the intrusion of a mass of igneous rock below the uplifted portion. In the present state of our knowledge it is

impossible to say whether the intrusion is the cause or the effect of the uplift, but at any rate it is clear that the two phenomena are intimately connected (Fig. 62*b*).

(3) *Kaibab Structure.*—This name is applied when the discontinuity of the strata is more marked : here there is on one side a fault of very large throw, without flexuring. The difference between this and the Uinta structure is only one of degree (Fig. 62*c*).

(4) *Basin-range Structure.*—Here flexuring is still less conspicuous, and the whole area is broken up by faults into blocks of varying shape and size, which are tilted at various angles. The general result of the action of denudation on a region of this kind is the production of a number of hill-ranges composed of a clearly marked escarpment and dip-slope, the crest of the escarpment running closely parallel to the bounding fault on the upthrow side. This type is sometimes spoken of as *block-structure* (Fig. 62*d*).

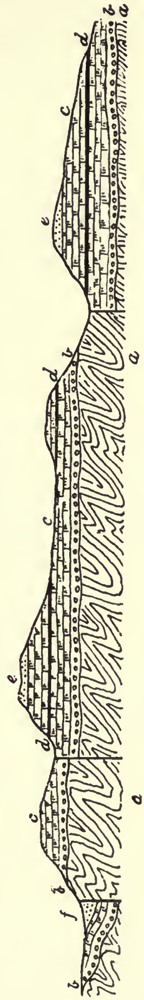


FIG. 63.—DIAGRAMMATIC SECTION ACROSS THE PENNINE CHAIN, FROM THE EDEN VALLEY TO THE RIVER TEES. Showing *block-structure*.

a, Lower Palæozoic rocks ; *b*, Basement conglomerate of the Carboniferous ; *c*, Lower Carboniferous ; *d*, Whin Sill ; *e*, Millstone Grit ; *f*, Permian and Trias.

Block-structure in Britain.—As before stated, structures of such simplicity are rare in Britain, owing to the extensive prevalence in this country of mountain-building movements and their attendant folding and faulting of the strata. However, block-structure prevails to a large extent in the Isle of Skye, where the plateau-basalts and the intruded sills are seen to be broken up into well-marked blocks tilted at various angles. This is significant, since the eruption of lavas from fissures instead of from volcanic cones is often an accompaniment of plateau-building movements, as in the Snake River plains of Western America and the Deccan plateau of Central India (see p. 202). Another good example is afforded by the fractures affecting the Carboniferous and older rocks of the Pennine chain in West Yorkshire, Durham, Westmorland and the east of Cumberland. The most important of these fractures are the Craven, Dent, Pennine and Tynedale faults, and these, with others of less importance, divide the country into a series of blocks at different levels. Conspicuous examples of fault-scarps are seen in the great scars near Settle, and in the Cross Fell range, which bounds the Eden valley on the east (see Fig. 63).

Horsts.—A study of differential movements has shown that certain well-defined blocks tend to stand up as hard and immovable masses, while the areas around them sink : these fixed masses are now generally

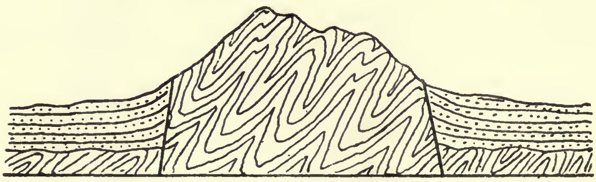


Fig. 64.—Horst Mountain.

This is the reverse of a rift-valley.

designated by the German term *Horst*, for which there is no satisfactory equivalent in English (Fig. 64). The Highlands of Scotland, to the north of the Grampian fault, and the Southern Uplands are good examples of horsts, while between them occurs the depressed area of the Central Valley. The Black Forest and Vosges blocks on either side of the Rhine valley may also be mentioned (Figs. 65 and 66). On a much

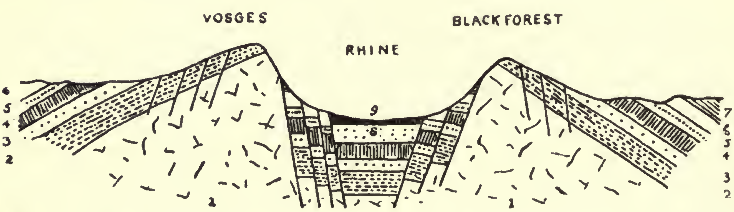


Fig. 65.—The Rhine flowing in a Rift-valley.

1, Granite ; 2–7, Mesozoic rocks ; 8, 9, Tertiary and Recent.

larger scale the African continent appears to be one of the most stable segments of the earth's crust, since it has apparently never been submerged since very early geological times. Horsts play a very important part in the economy of mountain-building movements, since they form fixed masses which largely control the direction and results of lateral thrusts, when these occur in the same area. This will be clearly seen in a later section, when the trend-lines of the Alpine and other mountain-chains are considered. The ultimate reason why some parts of the crust are more stable than others is not known, but it is probably connected with the development of dominant structure-lines at a very early period of the earth's history.

Rift-valleys.—Closely connected with block-structure and horsts are the remarkable long narrow sunken areas known as Rift-valleys or Graben. In these a strip of country has been let down between parallel

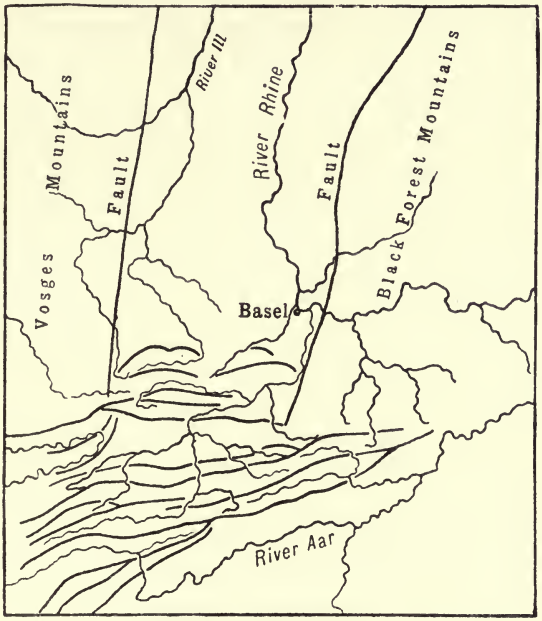


Fig. 66.—Map of Rift-valley of the Rhine.

The encroaching folds are seen to extend farther down the valley, being retarded against the horsts of the Vosges and Black Forest Mountains.

faults to form a depression, and in one case at least part of the floor of such a depression is far below sea-level. This is the great Rift-valley of Syria and Eastern Africa, one of the most remarkable physiographical features on the face of the globe. This depression begins in Northern Palestine; it forms the valley of the Jordan and the Dead Sea: the surface of the latter is nearly 1,300 feet below that of the Mediterranean. From hence it is continued down the Gulf of Akaba and the Red Sea. Nearly opposite Aden it turns to the south-west, and soon splits into two branches. The eastern branch runs nearly due south, and contains Lakes Rudolf and Stephanie: it appears to die out in the neighbourhood of Kilimanjaro. The western branch has a curved form, and gives rise to the great valley in which lie the Albert and Albert Edward Nyanzas, Tanganika and Nyassa. All these lakes are long, narrow and deep, indicating depressions in the floor of the valley, which appears to be undulating. The Victoria Nyanza, on the other hand, is wide and shallow, and lies on the plateau between the two branches of the rift-valley. The valley appears to be everywhere bounded by faults, which are usually complex, in the form of step-faults, and the dip of the strata forming the bounding blocks appears to be generally away from the rift, as if the latter had been formed by the collapse of the crown of an anticlinal arch.

The structure of the valley of the Rhine between the horsts of the Black Forest and the Vosges is very similar to this (Fig. 63), and the Central Valley of Scotland between the Highlands and the Southern Uplands is essentially a rift-valley. It is separated from the ancient gneisses and schists of the Highlands by the great Grampian fault, which has a maximum throw of some 14,000 feet. The Palæozoic rocks of the Southern Uplands are bounded on the north by another fault nearly parallel to the Grampian fault, while the floor of the valley between the faults is occupied by comparatively undisturbed Old Red Sandstone and Carboniferous rocks, many of which are volcanic. It may be mentioned in passing that igneous rocks and volcanoes, both recent and extinct, are abundant in the African rift-valley, and indeed it seems that the formation of rift-valleys is usually accompanied by volcanic action.

Submergence and Emergence of Land.—A detailed study of the lithological character and included organisms of the stratified rocks affords abundant evidence of the occurrence in past times of varying physical conditions, by which a large part of the earth's surface has been alternately raised into land and depressed below sea-level. Even at the present day there are to be seen along our coast-line clear indications of changes in the relative levels of land and sea occurring within recent times, and even now in progress. The most important physical features bearing on this point are the occurrence of raised beaches and lines of cliffs whose base is now above high-water mark : these indicate emergence, while submerged forests and drowned valleys show a movement in the opposite direction. In the case of submergence the evidence is naturally more difficult to trace clearly, since the rise of the water-level conceals the handiwork of the sea at lower levels. When a beach or shore-line sinks beneath the waves its characteristic features are hidden from our sight and soon destroyed by marine erosion, or covered up by deposition of sediment. In many cases, however, submerged terrestrial accumulations, and even the handiwork of man, can be clearly seen In some districts the submarine topography, as revealed by soundings, gives unmistakable evidence of submergence or *drowning* of land.

Changes of Level in the Baltic.—One of the most satisfactory cases of change of level occurs in the southern part of Sweden on the shores of the Gulf of Bothnia, and this is of classic interest, since it was investigated by Celsius and by Linnæus. The whole case is admirably summarised by Lyell in his 'Principles.' Early in the eighteenth century the apparent fall of the sea in Southern Sweden attracted the attention of Celsius, who estimated its rate to be about forty inches per century. He attributed the phenomenon to a general fall of sea-level all over the world, but it was soon pointed out that in other districts there was either no evidence of such a general fall, or even indications of a movement in the opposite direction. In 1749 Linnæus measured the distance between a large stone and the sea at Trelleborg, and in 1836 this distance was found to have decreased by 100 feet. Again, at Malmö, in the extreme south of Sweden, an ancient street was found 8 feet below sea-level. It was therefore evident that the movement was not a simple one of vertical uplift or subsidence of the country as a whole, but was in varying directions in different parts. According to Lyell's summing up of the case, Scania is sinking, whereas at Stockholm the land is rising at the rate of six inches per century, and at Gefle, still farther north, the rate of elevation is two or three feet per century. As will be seen later, in the north of Norway there is abundant evidence of an elevation of many hundreds of feet in recent times, so that it appears that the whole Scandinavian peninsula is undergoing a slow tilting movement—a lever, as it were, of the first order, with its fulcrum somewhere just to the south of Stockholm. It is also possible that, as suggested by Suess, the phenomena can be explained on the supposition of the slow uprise of an earth-wave of great wave length, consisting of an anticline and syncline, with its middle limb near the apparent fixed point. He refers the formation of this fold to the general contraction of the earth's crust.

Raised Beaches.—Where the relative movement of land and sea is negative according to the nomenclature adopted by Suess, we find old shore-lines above high-water mark. These raised beaches or strand-lines are characteristic features of high northern and southern latitudes, and are particularly well seen in Norway, where they are held to prove a recent negative movement to the extent of 600 feet or more. There has been much controversy as to the origin of the Scandinavian strand-lines, and Suess does not admit that they are due to an actual differential movement. He maintains, on the other hand, that they are the terraces of glacial lakes like those of Glenroy. An important objection to this idea is the fact that the terraces or beaches are found not only in the fjords, but also facing the open sea and even on islands, and the existence of a great mass of ice over the open Atlantic is at least very improbable. Sir A. Geikie has no doubt that the strand-lines are, in fact, ancient sea-beaches, and he points out important differences between them and the acknowledged lake terraces of the Glenroy type. Two quite distinct topographical forms may be recognised in the raised beaches of the far north. On the one hand are terraces of shingle and other material, just like modern beaches of accumulation on gently sloping coasts, and on the other hand narrow notches or shelves cut out of solid rock or boulder-clay, like the platforms which are so common on steep and rocky shores. These shelves are in Norway called *Seter*.

Round the Scottish coast there is a series of raised beaches at various levels up to 100 feet above present high-water mark. Of these, the most conspicuous occur at 100 feet, 50 feet and 25 feet respectively. The two higher ones date back to the Glacial period, as is shown by their organic contents and their relations to the boulder-clays and other drift deposits. The lowest beach contains a fauna like that of the present seas. The raised beaches are traceable more or less continuously all round Scotland except in the extreme north, but the upper one, or hundred-foot beach, is only found in scattered places. The middle and lower beaches are very conspicuous features of the west coast, especially on the shores of Loch Linnhe and many of the sea-lochs which open into it, and also in the Isle of Skye. Raised beaches have also been detected near Pentreath in Anglesey, on the shores of Morecambe Bay, and in Devonshire, Cornwall and the south of Ireland. One of these, in the neighbourhood of Cork, is clearly anterior to the oldest of the Irish boulder-clays.

Evidence of Submergence of Land.—Besides the very satisfactory case just described, there is to be seen on many coasts conclusive proof that the sea now stands higher relatively to the land than it once did. It is hardly necessary to enter into detail as to the nature of the evidence brought forward to prove this point. In some cases the lower streets of ancient towns are now at or near sea-level, or have been swept away altogether. On the west coast of Greenland Eskimo huts may be seen now standing in the sea, and so on. In many lands there exist traditions of former cities now below sea-level, and even legends of lost continents, such as Atlantis and the Land of Lyonesse. In some cases there appears to be some foundation for these stories, and the existence of the drowned city of Ys, in the Bay of Douarnenez in Brittany, seems to be well established. There is no doubt, however, that in some places coast erosion has produced effects which have been mistakenly put forward as proofs of submergence; and in other instances the evidence is capable of more than one interpretation. The loss of great tracts of land and thriving seaports in Eastern England seems to be entirely due to coast erosion.

Tempest Anderson, photo.

(I) TEMPLE OF SERAPIS, POZZUOLI.

(II) MISTI, NEAR AREQUIPA, PERU. A CONE COMPOSED OF ASH SHOWING THE CHARACTERISTIC CONCAVE CURVE.

Changes of Level in the Bay of Naples.—An interesting case of oscillation of levels, and one which has given rise to much discussion, is that of the so-called Temple of Serapis at Pozzuoli, near Naples (Plate XXIII (i)).[1] The chief remains of this building, which was probably a market rather than a temple, consist of three marble pillars about 40 feet high. Their surface is smooth up to 12 feet above the base; the next 9 feet are plentifully pierced by borings of *Lithodomus*; the remaining part of the pillars is untouched by boring animals. The pavement of the building is at the present time slightly below mean sea-level. Below this present pavement excavations in 1828 showed the presence of another at a depth of 5 feet. According to Lyell, the deposits which filled up the lower part of the building were composed of an alternation of calcareous sinter and volcanic ashes. The sequence of events here indicated is rather complex, but may be summarised briefly as follows. After the construction of the earlier pavement depression occurred, so that the building was reconstructed at a higher level, and then the great pillars were set up. Then deposits of sinter and ash were formed inside the building to a height of 12 feet, and at a still later period depression occurred to a depth of at least 20 feet. The lower portions of the pillars were protected by the sinter and ash, but a zone about 9 feet high was exposed to the action of marine-boring organisms, while the rest of the pillars were above sea-level. The most recent movement has been one of elevation, bringing the ground to its present level.

By some writers this has been brought forward as evidence of changes in the level of the sea. However, on other parts of the same coast-line there is evidence of similar depression and elevation to varying amounts, and it is evident that the movement was of the land, and not of the sea. Suess draws attention to the fact that Pozzuoli is situated in a highly volcanic district, and points out that it is only a mile or two from the Solfatara and Monte Nuovo, which were recently active. He attributes the movements to unimportant local risings and sinkings in a volcanic centre. Gunther,[2] however, has shown that the movements affect a much wider area than Suess is willing to admit, including the whole district of the Bay of Naples; and there is no doubt that the phenomena seen at Pozzuoli are indications of actual local disturbances and displacements of the earth's crust, acting in different directions at different times.

Submerged Forests.—Around the shores of the British Isles and elsewhere there are often to be seen beds of peat and vegetable soils containing stumps of trees in the position of growth, either between

[1] Lyell's *Principles*, 1868, vol. ii. p. 168.

[2] *Nature*, vol. lxix., January 21, 1904, p. 274; *Geographical Journal*, vol. xxii., August and September 1903, pp. 121, 269.

tide-marks or below the level of the lowest tides. In most cases these undoubtedly show submergence. It appears, however, that swamps may form behind shingle bars, at a level below that of the sea outside; if the shingle barrier is washed away and the swamp overflowed by the sea, a false appearance of submergence might be produced, so that the evidence from apparently submerged forests and peat-bogs must be received with some caution. Submerged forests have been observed at many points around the British coasts, and especially in Cheshire and Lancashire, on the shores of the Bristol Channel, along the English Channel, and near the mouth of the Tees. They are less common in Scotland, but some have been observed on the coast of Fife and elsewhere.

Drowned Valleys, Fjords and Sea-lochs.—On many parts of the coasts of Western Europe and elsewhere the sea runs far up into the land in long narrow inlets, which are called fjords in Norway and sea-lochs in Scotland. It is pointed out by Sir A. Geikie in his 'Scenery of Scotland' that the peculiar form of the sea-lochs of the west coast is popularly ascribed to differential erosion by the sea along alternating bands of hard and soft rocks, but that this idea is untenable, since the lochs are usually deeper inside than at their mouths, and the sea is quite unable to erode a deep basin of this sort. Again, the form of the contours below sea-level is exactly similar to those above; there is no break in the slopes at or near sea-level. This shows that the whole depth of the excavation must be due to subaerial denudation; that the sea-lochs are in fact drowned valleys. The great depth of many of them is very striking. As an example we may take Loch Etive, in Argyllshire. Soundings show that this loch is divided into two basins, one extending from the mouth to Taynuilt with a maximum depth of 35 fathoms, while the upper basin reaches the great depth of 76 fathoms. This loch is clearly a rock-basin, since the rocky barrier is conspicuously visible at Connel Ferry, and at low tide it forms a rapid called the Falls of Lora. A very similar barrier also exists at the mouth of Loch Leven at Ballachulish Ferry. The fjords of Norway show the same phenomenon on a much larger scale. The inner part of the Hardanger Fjord shows soundings up to 400 fathoms, while at its mouth the depth does not exceed 180 fathoms, and similar relations are shown in innumerable other cases. It appears, then, that these fjords and sea-lochs are valleys of subaerial origin which have been submerged, and they contain lake-basins which must have been formed in the same manner as the rock-basins of Loch Coruisk and others; that is, in the opinion of many authorities, by ice-erosion. We are not here concerned with the manner of origin of these basins, but only with the fact of their existence. It is significant that true fjords are only found in districts which have been recently glaciated. In other regions, such as Brittany, the north-west of Spain, the peninsula of Devon and Cornwall and South-west Ireland, there exist long inlets of the sea, the *Rias* of Richthofen, which on the map look much like fjords, but which possess an essentially different structure ; they are shallow, and not deeper inside than at the mouth. In a word, they are not rock-basins, and are the characteristic drowned valleys of non-glaciated regions.

On both sides of the Atlantic there are known to exist deep submarine channels usually in direct continuation of existing river-valleys, which are believed by some writers to be due to submergence, while others consider that they have been formed solely by deposition of the material brought down by the rivers while the land stood at or near its present level. A good example is the submarine cañon of the Hudson River, opposite New York, which can be traced for nearly 150 miles out to sea, down to the edge of the continental plateau. According to Professor Hull, the channel of the Tagus can be traced for fifty miles out to sea to a depth of 7,000 feet, and the Fosse du Cap Breton at the inner angle of the Bay of Biscay extends for thirty miles and is 600 fathoms deep. He regards it as the submerged channel of a river, possibly the Adour.

Mountain-building or Orogenic Movements.—In sharp contrast with the class of phenomena just described are the effects arising from movements of the earth's crust in which lateral or tangential stresses are involved. The origin and nature of these stresses will be considered more in detail in a later section : it will suffice for the present to say that the general result is compression and crumpling of the superficial layers of the crust, resulting in folding, faulting and overthrusting of the rocks, both stratified and unstratified. A minor but very important effect of such movements is the setting-up of dynamic metamorphism, often of a very high grade, and including such structural alterations as cleavage, schistosity and foliation, together with a partial or complete recrystallisation of the minerals constituting the rocks. The structures which result from these movements are various, and in some cases of an almost inconceivable complexity. In the introductory chapter of this work a brief account has been given of the simple types of folds and fractures, considered as units : it now remains to deal with possible combinations of these structures as exemplified in particular instances : from the study of certain cases it has been found possible to draw general conclusions on the mechanics of mountain-building.[1]

This well-marked compression and crumpling of the strata takes

[1] Heim, *Mechanismus der Gebirgsbildung*, Basle, 1878; Lapworth, 'The Secret of the Highlands,' *Geol. Mag.*, 1883, p. 120 *et seq.* ; Bailey Willis, *Thirteenth Ann. Rep. U.S. Geol. Surv.*, 1891–92; Mellard Reade, *Mountain-Building*, London, 1886.

place for the most part in somewhat sharply limited areas, which are generally of an elongated form, and often curved : these are commonly spoken of as zones of folding. At some period of their existence zones of folding usually form elevated regions, which when subjected to the action of subaerial agents of denudation give rise to typical *mountain-chains.* For this reason the movements which result in pronounced folding are spoken of as *mountain-building* or *orogenic.*

Types of Folding.—According to the nature and degree of intensity of the stresses involved, several distinct types of structure can be recognised. In some cases the pressure seems to have acted more or less equally from both sides, so that the resulting zones of folding possess a symmetrical structure, but much more commonly the structures are distinctly asymmetric, indicating that the pressure was greater in one direction : in such cases overfolding and thrusting are prominent, often leading to results of much greater complexity than

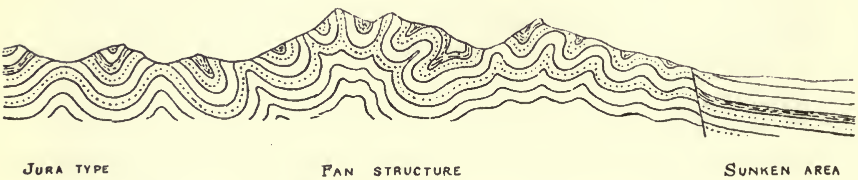


FIG. 67.—DIAGRAMMATIC SECTION OF A MOUNTAIN-CHAIN, SHOWING FAN-STRUCTURE.

in the former case. Perhaps the simplest case is where the transverse section of the folded region shows a succession of more or less regular anticlines and synclines, whose axes are parallel or nearly so, without notable overfolding or faulting. The classical example of a structure of this kind is afforded by the Jura Mountains on the borders of France and Switzerland (Fig. 67), but the most complete modern discussion of such a region is that given by Bailey Willis in the monograph before cited on the Appalachian chain, in the eastern part of the United States of America.

The Appalachian Chain.—The folded area is about 900 miles long, and varies in width from 50 to 125 miles. It is bounded on the east by ancient crystalline gneisses and schists, and on the west by the horizontal strata laid down in the great inland sea of Palæozoic and Mesozoic times, of which it appears to have formed the littoral region, as shown by the shallow-water character of the strata which compose it. The folded area has evidently long been a region of great sedimentation, and, as we shall see later, this is a significant fact. In the Appalachian chain the phase of deformation produced is that which follows compression : the arc, once covered by the strata, has been shortened, and the length in excess taken up by folding, and in a minor degree by faulting. The relief of the ground is closely connected with its geological structure, and the whole is definitely known as the Appalachian type.

The Alpine Mountain-chain.—Most mountain systems are much more complex than the Appalachians, and present a much greater variety of structure. No region of this kind has been studied so exhaustively as the Alps, and the phenomena there displayed may be briefly described as a type. The origin of the Alpine chains is undoubtedly to be referred to great thrusting movements, acting on the whole from south to north, with some local deviations. These thrusting movements resulted in the production of numerous parallel folds, which generally assumed a curved form, owing to the existence of horsts. These horsts cause the folds to deviate from the general direction, which is at right angles to the pressure, and the arrangement of the Alpine folds is a curved one. It is to be noted that the term Alpine system is used by modern writers in a very extended sense, to include not only all the mountain-ranges running from the south-east of France through Switzerland and North Italy into the Tirol and the south-west of Austria-Hungary, but also the chains of the Carpathians and the mountains of Transylvania. This chain is also continued across the Iron Gate of the Danube, forming the Balkans; but here the direction of thrust has changed, so that the Balkans are overfolded from the north. The Apennines, and the Atlas Mountains in Northern Africa, are also members of the same great mountain-chain, which in its present form is of Tertiary age.

The structure of the Alpine mountain system and the mutual relations of its various parts can perhaps be most clearly seen in the northern part of the Austrian Empire in Moravia and Austrian Silesia, where the arrangements are simpler than in Switzerland or France. According to Suess and other recent writers, the whole may here be divided into three parts, from north to south, as follows: (1) the Foreland, (2) the chain of the Carpathians, (3) the sunken area of Hungary.

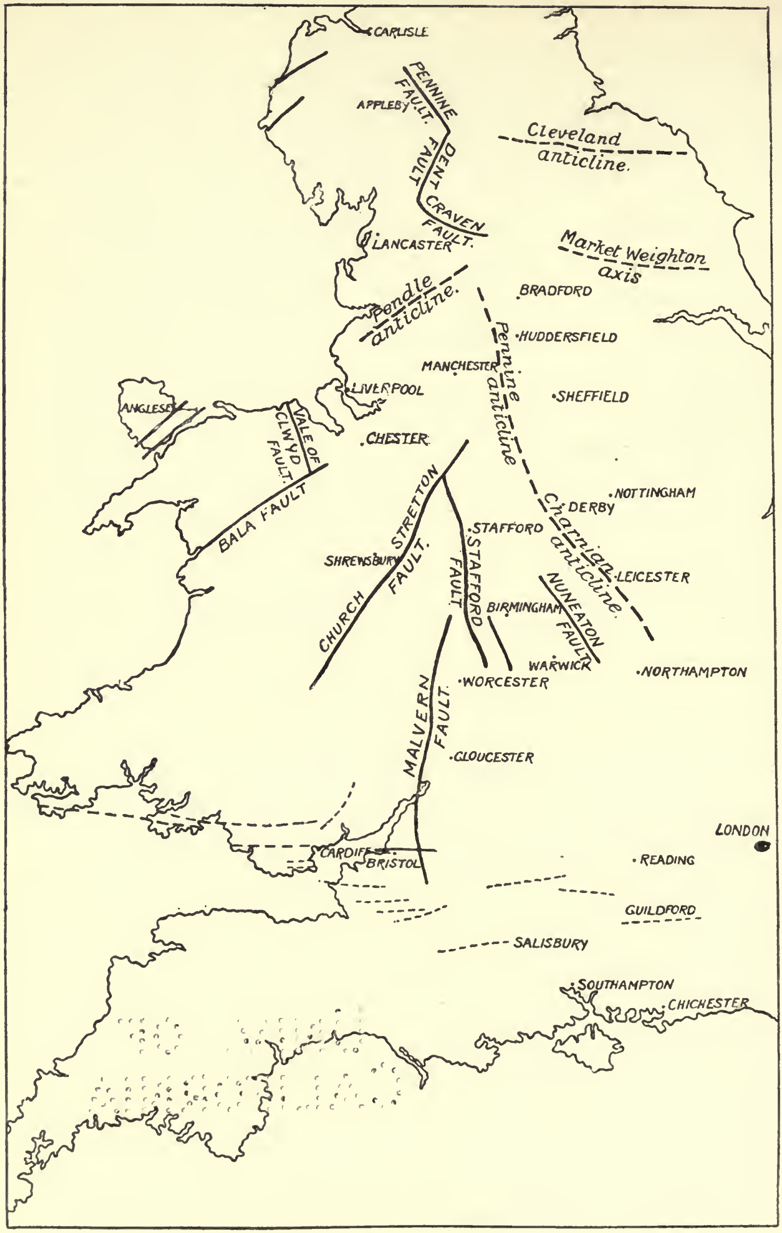
The name *Foreland* is given to the region composed of masses of older rocks which limited the extent, and to a certain degree controlled the form, of the Alpine system towards the north. In the area under consideration the foreland consists of three parts : the Russian platform to the east, the Sudetes Mountains in the centre, and the Archæan massif of Bohemia farther west. The Russian platform is composed of generally horizontal strata, while the Sudetes are a folded mountain-chain of much older date. The folds of the Carpathians have encroached on these structures, so that the horizontal rocks of the Russian platform and the Silesian coal-field are known to be continued under the folded chains, which here strike east and west, and can be seen to override the older folds of the Sudetes, which have a N.W.–S.E. strike. Farther to the west similar relations hold (see Fig. 66); and in Western Switzerland the structure is further complicated by the interposition of the Jura region of symmetric folds, and a broad area of low relief, the plain of Central Switzerland, between the Alps proper and the foreland.

The Alps.—Under this general designation is included the great mass of mountains forming the south-east of France, the south and east of Switzerland, part of Northern Italy and the Tirol. The Carpathians possess the same general structure, and are, as before pointed out, the direct continuation of the main zone of folding towards the east. By most recent writers the Alps of Switzerland are divided into two parts: (1) the Pre-Alps, which extend from Dauphiné past the Lake of Geneva towards the north-east, and consist of Secondary and Lower Tertiary rocks, very highly folded and much overthrust; (2) the High Alps, comprising the most elevated portions of the mountain region, such as the Mont Blanc massif, the Valais Alps, and the Bernese

FIG. 68.—MOUNTAIN RANGE CARVED FROM A FAN-STRUCTURE.

Oberland. Of late years there has been, and still is, much controversy as to the actual structure of these two regions; in many parts there is evidence of extraordinary complexity, and numerous interpretations have been put forward by Escher von der Linth, Baltzer, Renevier, Heim, Rothpletz, Schardt, Bertrand, Lugeon and many others.

It has been commonly believed that the structure of the main chains of the Alps may be interpreted as what is usually known as fan-structure; that is to say, they consist of a series of great arches, each composed of a number of subsidiary folds, whose axes tend to dip inwards towards a central line. The result of the denudation of such a fan, or anticlinorium, is to expose the oldest rocks along the central parts of the chain, while the flanks show narrow synclinal bands of newer rocks wedged in among the older ones and apparently overlain by them (see Fig. 68). Diagrammatic sections across the Alps, drawn from the point of view of this conception, will be found in almost all text-books, but of late it has begun to appear that this explanation will not account for all the facts. Recent work in the Western Alps and elsewhere indicates the important part played by recumbent folds with nearly horizontal axial planes, which have in some cases been torn away from their *roots* and carried for great distances over the



MAP OF THE PRINCIPAL FOLD-LINES AND FAULTS OF NORTHERN ENGLAND AND WALES.

After Sir A. Strahan, Rep. Brit. Assoc., 1904, Plate viii (with slight alterations and additions). Continuous lines are faults, broken lines are anticlines.

neighbouring rocks. In other cases the connexion with the roots of the fold is still visible. On the north side of the main chain there are folds of smaller amplitude, in which the rocks have not moved far from their original position. These are called autochthonous folds (see Fig. 69). By this hypothesis it appears that the rocks of the Pre-Alps

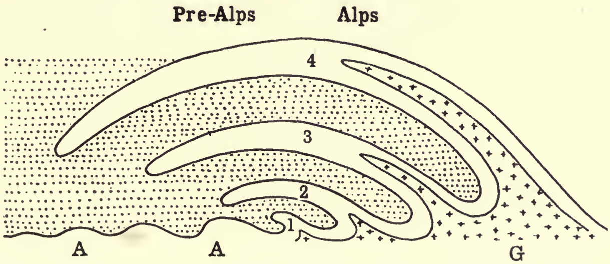


FIG. 69.

A, *A*, Autochthonous folds ; 1, 2, Sheets with external roots ; 3, 4, Sheets with internal roots ; *G*, Gneiss. (After De Lapparent.)

now possibly occupy a position far from where they were originally formed, and it is suggested that some of them have actually passed right over the crystalline massif of Mont Blanc on the way to their present position in the Chablais, the Dent du Midi and the Dent de Morcles.

FIG. 70.—ISOCLINAL FOLDING.

The Plains of North Italy and Hungary.—These represent the region of subsidence which always occurs on the inner side of a folded chain. The rocks here are in a state of tension, due to the forward movement of the folded part of the system, and they tend to settle down in blocks, bounded by faults, so that the structure approximates to that of a plateau. Lombardy and Hungary thus form land areas of low elevation and low relief. But in other cases the subsidence has been so great that large areas have sunk below sea-level : the Adriatic, Tyrrhenian and Ægean Seas are of this nature, and they are closely connected with the formation of the Alpine and allied chains in Tertiary times.

Systems of Folding.—Turning now to a consideration of more general cases, we find that according to the arrangements of the folds several distinct types of structure can be recognised. As before stated, a series of parallel anticlines and synclines which are symmetrical, or nearly so, is distinguished as the Jura or Appalachian type. When the thrust is more distinctly unilateral, so that overfolding to one side is pronounced,

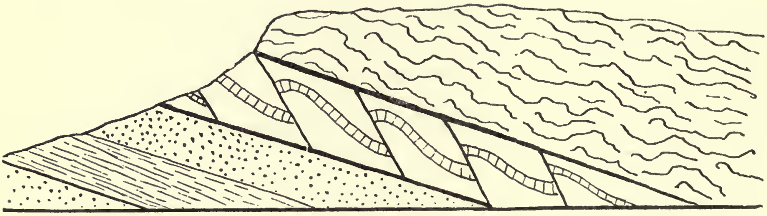


FIG. 71.—IMBRICATED STRUCTURE: NORTH-WEST HIGHLANDS.

the structure is known as *isoclinal* (Fig. 70). When the pressure has been intense the folds are often ruptured along their middle limbs, and the blocks thus separated are thrust over one another something like a pack of cards: this is known as *imbricated* structure, and the divisional planes between the individual blocks, which are really of the nature of minor thrust-planes, are sometimes spoken of as *soles*. This structure is well exemplified in the North-west Highlands of Scotland, where there occur several series of imbricated blocks, one above the other, separated

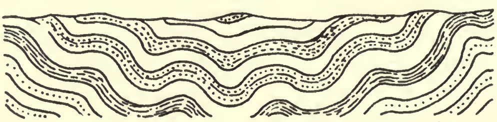


FIG. 72.—SYNCLINORIUM.

by major thrust-planes, which have often carried the whole series for some miles to the west of their original position (Fig. 71).

An assemblage of folds having the general disposition of an arch is called an *anticlinorium*; the fan-structure previously described as characterising certain parts of the Alpine chains is merely an exaggeration of this, where the squeezing has been so intense that the middle part of the folded zone has bulged out over the outer parts (see Fig. 68). In a similar way we may have a *synclinorium*, a series of folds which, speaking generally, form a syncline (Fig. 72). The structure of North Wales, between the Menai Straits and Shropshire, belongs to this type.

Examples of Folding in the British Isles.—For the formation of a folded area of Jura or Appalachian type it is essential that the strata should be fairly uniform in character over a considerable area, and that the pressure should also act with a certain amount of uniformity. These conditions do not seem to have been attained anywhere in the British Isles, where the folded regions always show considerable complexity of structure, and there is generally much faulting and thrusting where the movements have been at all intense. The important disturbances which affected the strata of the south of England in Middle Tertiary times have given rise to structures of moderate simplicity, so far as concerns the Mesozoic and Lower Tertiary rocks. The south and south-east of England consists, broadly speaking, of two anticlines and two synclines with parallel axes. The synclines form the London Basin and the Hampshire Basin: these are separated by the broad arch of the Wealden uplift, which is itself probably an anticlinorium, and is continued westward through the Chalk Downs of Hampshire: the southern anticline of the Isle of Wight and the Isle of Purbeck has been in part dissected by the sea, but enough remains to show its original structure. This anticline is markedly asymmetric: in the Isle of Wight the northern limb is vertical, and in the Isle of Purbeck the beds are even inverted, the anticline passing over into a reverse fault or thrust-plane.[1]

One of the most conspicuous anticlinal arches in the British Isles is that which forms the southern part of the Pennine chain in Derbyshire and the south of Lancashire and Yorkshire. The movement which gave rise to this uplift is of an age intermediate between the Carboniferous and the Permian, since the Carboniferous rocks are folded, while the Permian strata lie almost horizontally on their denuded edges. Of approximately the same age is the folding which has affected the Devonian and Carboniferous strata of Devonshire, and a good example of isoclinal folding is to be seen on a small scale in the cliffs and on the beach at and near Ilfracombe. Reference has already been made to the imbricated structure and thrust-planes of the North-west Highlands, and these will be described more fully in the stratigraphical section of this book. These are developed on a great scale, but some of the thrust-planes of the Alps and Scandinavia are of even greater magnitude. In most of the cases referred to, the upper blocks have moved forward farther than the lower, but in explanation of certain peculiarities of structure and outcrop observable in the English Lake District it has been suggested that the lower blocks have moved forward farther than the upper ones. This may also be expressed by saying that the

[1] Strahan, 'Guide to the Geological Model of the Isle of Purbeck,' *Mem. Geol. Surv.*, 1906. This small pamphlet may be strongly recommended to students.

upper blocks have lagged behind the lower (Fig. 73). The planes along which relative displacement has occurred are therefore called *lag-planes*. In this connexion it may be observed that the term *overthrust* is founded on an assumption that the upper blocks moved forward: this is not in all cases demonstrated, and a backward movement of the lower blocks, or *underthrust* in the opposite direction, would produce precisely the same effect, so far as the resulting geological structure is concerned.

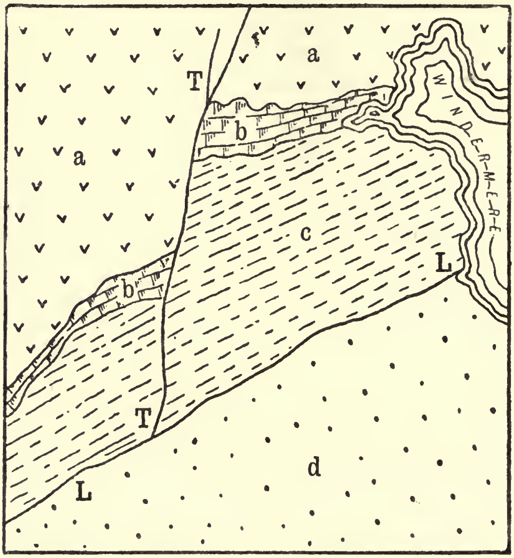


FIG. 73.—MAP SHOWING FAULTS TO THE WEST OF THE HEAD OF WINDERMERE, CUMBERLAND. (After Marr.)

a, Volcanic Rocks; *b*, Coniston Limestone; *c*, Coniston Flags; *d*, Coniston Grits; *L L*, Lag Fault; *T T*, Tear Fault.

Origin of Mountain-building Movements.—One of the most difficult tasks of modern geology is the elucidation of the causes which have given rise to the folds and fractures of the earth's crust. These were formerly attributed to simple contraction consequent on cooling, principally due to the decrease in volume of the nucleus, which was supposed to shrink away from the crust, leaving the latter unsupported, with a consequent tendency to wrinkle. It is now considered, however, that this cause is inadequate to produce all the effects observed.

Extensive folding always takes place in long narrow zones generally possessing a curved form, and from a study of the types of sedimentary strata composing such areas a generalisation has been drawn. It is found that folded zones are composed of enormous thicknesses of comparatively deep-water sediments of very uniform lithological character, usually without notable interruptions or unconformities, while in the undisturbed areas the same formations are represented by a much less thickness of strata, of shallow-water character, and with frequent intercalations of fresh-water and terrestrial deposits. Great thicknesses of uniform strata can only be laid down in an area which is sinking concurrently with the deposition, so that the depth of water remains constant. It is concluded, therefore, that zones of folding begin their existence as long narrow depressions of the crust, to which Dana long ago gave the name of *geosynclinals* (Fig. 74). In more recent times these conclusions have been formulated as a law, viz. mountain-chains arise on the sites of geosynclinals.

A notable feature in the distribution of zones of folding is that they often occur near the boundaries between the great continental

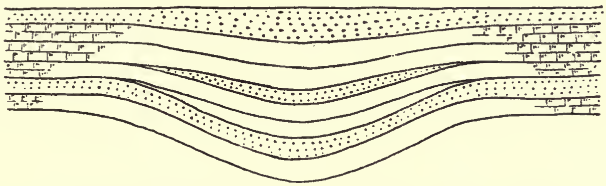


FIG. 74.—DIAGRAM OF A GEOSYNCLINAL. (After Haug.)

masses and the ocean-basins; this is specially noticeable in the case of the Pacific, where the greatest depths of the ocean are found in the peripheral parts, in front of the great mountain-chains, whereas the central portions are much shallower. In other cases folded regions occur between the two continental masses, as in the case of the Alpine system of the Mediterranean region.

According to this view the earth consists of certain stable blocks, the continental masses, separated by long narrow areas where the crust is much weaker, the geosynclinals. When the relative positions of the continental masses undergo alteration, the geosynclinals are squeezed between them, so that they are compressed, and the strata of which they are composed are crumpled and tend to bulge outwards. Thus, for example, the Mediterranean region is regarded as having been squeezed in Tertiary times between the Eurasian and the African continents, so that the distance between the edges of the stable blocks became less, and the length in excess was taken up by the folding of the Alpine and other chains. The shortening of the strata forming the Alps and Jura is estimated by Heim at seventy-four miles, while the shortening in the Appalachian chain was about forty-six miles. The zones of folding are thus, as it were, squeezed between the jaws of a vice, formed by the approach of two continental masses.

Causes of the Movements.—Three principal explanations have been put forward to account for the movements of segments of the globe in the manner thus stated: (1) sinking under gravitation, (2) flow of superficial masses of the crust, (3) isostasy. The first and second of these are probably inadequate to account for the phenomena observed, and the third is the one which finds most favour at the present time. By isostasy is meant that condition of form to which the force of gravitation tends to restore planetary bodies, whether homogeneous or not. Every body in a condition of rotation about an axis must possess a form of equilibrium, and until this equilibrium is attained strains are set up and deformation occurs. When this state is reached, if the distribution of matter remains unchanged no alteration of form will occur. But this is not the case with the earth; the land masses are destroyed by denudation and the material thus removed is deposited in the oceans, thus giving rise to a redistribution of mass and a disturbance of the form of equilibrium. Hence the heterogeneous segments will undergo relative displacement, and the weaker zones between them will be squeezed and compressed in some cases, and possibly stretched in others. This latter condition has been less thoroughly investigated, but its possibility should be taken into account. The sum-total of all the movements and disturbances in rocks after their deposition is called *diastrophism*, and of this isostasy may be regarded as the most important phase.

CHAPTER XII

VULCANICITY

Connexion between Earth Movements and Vulcanicity.—As explained in the preceding chapter, the greater movements of the earth's crust are accompanied by that class of phenomena to which the general name of vulcanicity may be applied. This term is here used with a somewhat extended meaning, including not only the phenomena shown by volcanoes in all their forms, but also the manifestations of igneous activity which occur within the deeper layers of the earth's crust, and give rise to what are conveniently known as the intrusive rocks. Volcanoes and intrusions are phases of the same form of activity under somewhat different conditions, and cannot logically be separated.

The question of the exact mode of action of volcanoes and igneous activity generally must be regarded as still undecided, and a summary of some modern views on the physics and mechanics of vulcanicity will be given later. But whatever may be the proximate cause, it is clear that the ultimate cause is to be sought in the movements of the crust which are known to have occurred at various times in the past, and to be still occurring. It has already been shown that these crust movements tend to propagate themselves in the form of waves, which result in the formation of folds in the strata, and of corresponding lines of weakness parallel to these folds. Volcanoes also, as can be seen from a map of their general distribution, tend to occur in lines which follow the forms of these folded areas, and are rare or even absent in districts which are not folded. This is too strongly marked to be merely a coincidence, and it has also been shown by Bertrand and others that periods of great vulcanicity correspond in time with periods of great earth movement. The two classes of phenomena are thus seen to coincide both in time and space, and the study of one naturally follows that of the other.

Products of Volcanoes.—The products of vulcanicity may be emitted in the gaseous, liquid or solid forms. They vary much in character in different cases, and also during different phases of the activity of the same volcano. It would be easy to construct a very long catalogue of substances which are formed in connexion with volcanic eruptions, but many of these are of little or no importance, and may for our present purpose be disregarded. In the case of many of these rare substances it is also difficult to determine whether they are actual and original products of the volcano itself, or whether they have been formed by subsequent changes and the introduction of material from outside sources. It is only when any substance occurs repeatedly and in large amount that we can be quite sure that it is a true and characteristic product of the actual eruptive activity of the volcano.

It is most convenient to begin with the gaseous products of eruption, since they may be regarded as in some way partaking of the nature of cause as well as of effect. It is the evolution of gases on a large scale which, in the majority of cases, if not in all, is the actual dynamical agent by which the liquid and solid products are raised to the surface or ejected from the crater. The extreme importance of water in connexion with the phenomena in question will be considered in a subsequent section, when we come to deal with the causes of vulcanicity. Steam is emitted in vast clouds during nearly all eruptions, and it evidently forms the motive power of the explosive activity which is so common a feature. In the later stages of the life-history of many volcanoes, as will be seen in the sequel, steam and hot water are the sole products.

The presence of hydrogen has been noted during many eruptions, and in one or two cases oxygen has also been stated to occur: this has been supposed to indicate that the constituents of water may be dissociated in the magma: if so, their sudden recombination on a fall of temperature would also give rise to explosive energy. Hydrocarbons occasionally occur, especially marsh gas, and the combustion of these hydrocarbons and of hydrogen gives rise to the pale, lambent flames which are sometimes seen during an eruption. These flames are quite unimportant, and are the only instances of true combustion connected with vulcanicity.

Gaseous compounds of sulphur are very common, especially sulphur dioxide and sulphuretted hydrogen. These and other gases, by their mutual reactions, give rise to the deposits of sulphur which are so characteristic of volcanic districts. Some, however, of these so-called deposits of sulphur which have been described by non-scientific travellers are found really to consist of ferric chloride, which is very similar in appearance. This is produced by reaction between the iron compounds of the lava and the hydrochloric acid which frequently occurs in volcanic vapours. Sublimations of crystalline ammonium chloride are often found in craters, due to deposition by vapours, and the occurrence of similar deposits of sodium chloride has been cited in support of the idea that eruptions are due to access of sea-water to heated material.

In a few instances boric acid is found as an important constituent of volcanic vapours. This, however, occurs under special circumstances, and will be dealt with more fully in a later section.

The only remaining gaseous product which it is necessary to mention is carbon dioxide, which is commonly given off in large quantities during the very latest phase of the activity of a volcanic district. In a later section examples will be cited of the occurrence of these various constituents, and it will be shown that each indicates more or less definitely a stage in the life-history of a volcano.

Turning now to the liquid products of eruption, we find that they are for all practical purposes only two in number, viz. water and lava.

During the eruptions of normal volcanoes the temperature is so high that all the water is given out in the form of steam, but so soon as this steam comes in contact with the colder layers of the atmosphere it is condensed and descends again in the form of rain. Torrential rains are a very common accompaniment of great eruptions, and they often do more damage than the showers of ash or streams of lava. Sometimes these heavy rains, falling on accumulations of fine ash and dust, produce gigantic flows of mud which nothing can withstand. It was in this way that Herculaneum was destroyed. An eruption may also produce destructive floods in another way; many of the greater volcanoes of the world rise above the snow-line, and are thus sometimes capped by great quantities of snow and ice. If this is suddenly melted, great floods may be produced. In 1877 a stream of lava overflowed the crater of Cotopaxi, and melted some of the snow and glaciers near the summit.[1] The result was a great flood, which travelled for an immense distance at the average rate of twenty miles an hour, and devastated much of the surrounding country. Since some heavy machinery from a cotton mill was carried nearly thirty miles, the geological effect of such a flood must be very great.

Water produced in this way cannot, however, be regarded as a true and direct product of volcanic action, though its ultimate geological effect is much the same as if it was actually poured out of the crater in streams. There are cases of true eruptions in which water in the liquid state is the most important, or the only, product. These include such phenomena as geysers, hot springs, mud-volcanoes and so forth. These, again, are manifestations of expiring activity, and will be described in due course.

The other liquid product, lava (Plate XXV), is of a much more complex character. It is of the greatest geological importance, since it is the raw material of all the igneous rocks, both extrusive and intrusive. The study of the nature and composition of these rocks

[1] Whymper, *Travels among the Great Andes of the Equator*, London, 1892, p. 124.

forms the most important part of the science of petrology, but as this requires separate treatment, it must suffice for the present to say that lava may be defined as molten rock-material. The degree of fluidity of a lava depends very largely on its composition. An acid lava, when raised above its melting-point, remains very viscous for a long range of temperature, while a basic lava under like conditions quickly becomes highly mobile. This has a very important bearing on the forms of mountains built up of lava-flows.

The majority of volcanoes eject more or less of their products in the solid form, and the nature of these varies to some degree (Fig. 75). It is obvious that at the first formation of a vent, the material most likely to be thrown out will consist of fragments of the rock through which the opening has been made. Some of the crater-lakes of the Eifel are surrounded by a low ring mainly composed of fragments of the country rock, a slate of Devonian age, and many other volcanoes

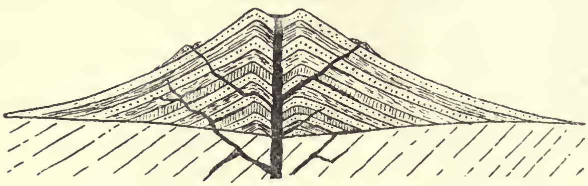


FIG. 75.—SECTION ACROSS AN IDEAL VOLCANO.

occasionally throw up fragments which have been torn from the sides of the pipe. These fragments are often highly metamorphosed. A good example is afforded by the blocks of altered limestone which are found at Vesuvius, and often contain rare minerals.

By far the most important of the solid products consist of lava-material, which has either solidified before ejection from the crater or has done so during the process. If liquid lava is carried up into the air in a finely divided state by explosive action, it will be cooled very rapidly and will reach the ground in a solid form. More important even than this is the material which solidifies within the crater and pipe of the volcano. If a volcano has been quiescent for a time a thick crust will form over the lava-reservoir, and the first effect of renewed activity will be the breaking up and blowing out of this crust. It is usually ejected as angular fragments of varying size, and forms the material known as agglomerate or volcanic breccia, which is so characteristic of the explosive type of eruption.

Even when a volcano is in a more or less continuous state of activity, with molten lava in its crater freely exposed to the air, a solid crust is constantly being formed and broken up again by the circulation

Tempest Anderson, photo.

(I) ETNA, LAVA OF 1886.

Tempest Anderson, photo,

(II) CORDED LAVA: MYVATN DISTRICT ICELAND.

of convection currents which goes on in the lava. This formation and breaking up of crusts has been observed again and again in the case of the great craters of Hawaii and many others. When the activity becomes rather greater than usual, that is, when an eruption occurs, some of this solid material is blown up into the air and falls beyond the limits of the lava-lake in the crater. In this way large cones may be built up (see Plate XXIII (ii)).

Special names are applied to this class of solid product according to its character: when it is very vesicular and, in fact, consists of the solidified froth and scum from the surface of the lava, it is called *pumice*, especially when of acid composition and so full of cavities as to float on water. Pumice really consists of glass of specific gravity about 2·5, and its apparent lightness is entirely caused by its spongy, cellular structure, which is due to the inclusion of a large amount of steam and gases in the lava from which it was formed. The term *scoria* is used for material of a rather more cindery nature and usually of more basic composition. It has essentially the same origin as pumice, and the slight differences are due to variations in the character of the lavas from which the two are derived. The name of *lapilli* is often applied to small stony masses varying from the size of a walnut to that of a pea or rather less. If the material is still more finely divided it is spoken of as volcanic sand or dust, and the latter is often in the very finest state of division, so that it is carried in the air for immense distances. Masses of volcanic dust, especially if partially or wholly solidified, are often designated *tuffs*. It is better to restrict this term to those accumulations which have subsequently become consolidated. Many of the above described materials are frequently spoken of rather vaguely as volcanic *ashes*. The term has no very precise meaning, but usually seems to imply a moderately fine state of division. *Bombs* are masses of lava, usually of a somewhat rounded form and often of considerable size. They are generally ejected in a more or less viscous condition, and become rounded during their passage through the air.

Fissure-eruptions.—The simplest, and in some respects the grandest, type of extrusion with which we are acquainted is one which is in no way connected with a volcano in the ordinary sense of the word. In some parts of the world there occur enormous masses of lava, commonly basalt, in horizontal flows, which show no relation to cones or craters of the usual kind; they are, however, visibly connected with vertical walls or dykes of similar rock, filling fissures in the underlying strata, which clearly served as channels for the uprise of the lava. These fissures are usually sensibly parallel over large areas, and are due to crust-movements on a large scale. Their existence is accounted for on the supposition that they are formed in regions where the crust is in a state of tension due to stretching.

This type of eruption was first clearly described and explained by von Richthofen in the case of the Snake River plains in the Great Basin region of North America. He called attention to the complete absence of cones and craters, and suggested the term 'Massive Eruptions.' They are now commonly spoken of as 'Fissure Eruptions,' and the resulting lava-flows are often called 'Plateau Basalts.'

The basalts of the Snake River plains cover an area of some 200,000 square miles, and their maximum thickness is about 3,000 feet. The Deccan plateau in Central India is larger still, and if certain outlying patches are taken to indicate former extension, it once covered 400,000 square miles of the Indian peninsula. But the lavas are thickest, nearly 7,000 feet, on the west coast in the neighbourhood of Bombay, and this suggests that they once extended to a much greater distance in this direction.

The most interesting development of fissure eruptions is that which gave rise to the basalt-plateau of North-west Europe and the Arctic islands. Extensive remains of these lavas are still found in the north-east of Ireland, the Western Isles of Scotland, the Faroes, Iceland, Spitsbergen, Jan Mayen, Franz Josef Land, &c. In some of these regions, especially in Iceland, the modern eruptive activity may be regarded as a direct continuation of these fissure-eruptions, slightly modified in character.

The basalts occur in distinct flows, usually with slaggy or cindery surfaces above and below; they very often show a marked columnar structure in the middle of the flows. However, many of the best-known examples of columnar jointing, such as the Giant's Causeway, Fingal's Cave in Staffa, and others, appear to be intrusive sills, injected into the lavas at a later date. Individual flows rarely exceed 40 or 50 feet in thickness, and they are often separated by remains of surface soils, indicating the lapse of a considerable time between successive eruptions. These old soils often contain plant remains and land shells, which fix the geological age of the eruptions. The lavas are generally highly vesicular or amygdaloidal, but there is a complete absence of the products of explosive eruption, except occasionally at the very base of the series, where a little agglomerate may be formed as a result of explosions during the opening of the fissures.

The Icelandic Type.—Closely related to fissure-eruptions is the form of vulcanicity which can now be seen in Iceland, and this presents several peculiar and interesting features. The volcanoes of this island have been carefully studied by Thoroddsen.[1] This author recognises three different kinds of eruptive vents, viz. (1) cones built up of both ash and lava; (2) cones built up of lava alone; (3) chains of craters.

[1] *Geographical Journal*, vol. xiii., 1899, p. 500.

The first two correspond closely with the Vesuvian and Hawaiian types, presently to be described; but the third kind is by far the most common. In the south of Iceland all the volcanoes are arranged along fissures running south-west and north-east; in the north of the island the fissures run north and south. The chain-volcanoes consist essentially of a large fissure along which are numerous small ash cones usually not exceeding 350 feet in height, and often very steep, with craters at the top. Sometimes the cones are separate and distinct, but commonly the point of eruption moves on, so that the rings intersect. Occasionally enormous floods of lava are given out from these crater-chains, as in the well-known case of Laki in 1783, when two separate streams of basalt flowed for 40 or 50 miles, with maximum widths of 15 and 7 miles respectively. Sometimes also flows of basalt issue from fissures without cones: these are generally small, but one such fissure is 20 miles long and has poured out sufficient lava to cover 270 square miles.

Volcanic Cones.—In most cases the centre of activity is still more localised, and may be regarded as concentrated at a point instead of being distributed along a line. When this occurs we get what is commonly known as a volcano, and these true volcanoes usually build up some kind of a cone or hill of accumulation round the orifice. The structure of this cone depends on the nature of the material ejected, and its size on the magnitude and duration of the eruptive activity.

Material may be ejected from volcanoes in the gaseous, liquid or solid form. The first of these can play no constructive part, but acts chiefly as a motive power; it is also at times destructive, as will be seen later; matter in the solid state, and certain of the liquid products when consolidated, are constructive, and build up the cone.

In a few cases the whole history of a volcano seems to be confined to a single explosion, which simply drills a more or less round hole through the crust without any further action. This leaves a hollow or crater surrounded by a low ring of fragments of the country rock. Such explosion-craters are often occupied by lakes, as in the Maare of the Eifel district in Germany. Usually, however, activity lasts longer than this. Sometimes a single phase of activity may give rise to a considerable cone, as in the case of Monte Nuovo, near Naples, which is 440 feet high, and was formed in two or three days, in the year 1538. Such youthful cones almost always consist entirely of fragmentary material, and the outpouring of lava belongs to a later stage in the history of the volcano. A very common result of the uprise of lava in an ash cone is the breaking down of one side of the crater, owing to the weight of the molten mass within. Such 'breached cones' are well seen in Auvergne.

When the activity of a volcano is long-continued it will eventually build up a very large cone, and these large cones are usually composed of both fragmentary material and lava; in a few cases, however, they consist of lava with little or no admixture of ashy matter. Most of the great volcanoes of the world belong to the former class, and their eruptive processes include both explosions of gas and vapours, and the upwelling of lava. Good examples of such cones built up by often-repeated eruptions are afforded by the great volcanoes of the Andes, the highest volcanic mountains of the world. Their structure is usually very simple, and many are so high that in their later stages lava has rarely reached the lip of the crater, and the upper part of the mountain is chiefly composed of ash. The best European example of a volcano of this type, though on a smaller scale, is Stromboli, which erupts gently every few minutes.

Vesuvius.—The history and structure of most great volcanoes is not so simple as this. As is well known, many of them have long periods of quiescence, which are frequently succeeded by eruptions of great violence. In fact, it may be taken as a general rule that the

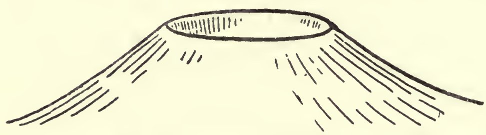


Fig. 76*a*.—Probable Appearance of Vesuvius before a.d. 79.

longer the period which elapses between two eruptions, the more violent will be the eruption when it does occur. This is well illustrated by the history of Vesuvius since the beginning of the Christian era.

Before this time the general appearance of the mountain must have been very different from what it is at the present day. It consisted of a simple, steep-sided cone with a very large crater, and was apparently extinct (Fig. 76*a*); there appears to have been no record or tradition of an eruption from it, and probably only a few recognised its volcanic nature. In the year 79 a.d., after a series of violent earthquakes, a great explosion occurred, and the towns of Herculaneum and Pompeii, among others, were completely buried by the debris. The general effect of this great explosion was to blow away a large part of the walls of the crater. Part of the crater-ring was left standing, and now forms the crescent-shaped elevation which partially surrounds the modern cone of Vesuvius, and is known as Monte Somma (Plate XXVI (i)). The products of this eruption were entirely of a fragmentary character, and no lava was emitted (Fig. 76*b*).

Since that time Vesuvius has been in a state of more or less continuous activity, although the interval between successive eruptions

PLATE XXVI

Tempest Anderson, photo

(I). THE EDGE OF THE CRATER. MONTE SOMMA.

Tempest Anderson, photo.

(II) VULCANELLO, FROM THE SEA.

has often been very long. In most cases lava has been discharged as well as ashes and dust, and the cumulative effect of all these eruptions has been to build up a newer cone and crater inside the broken ring of Monte Somma (Fig. 76*c*). The general effect of these eruptions has been sometimes constructive and sometimes destructive, and the height and general form of the mountain have undergone considerable modifications. Lava-streams have often issued from cracks in the

FIG. 76*b*.—PROBABLE APPEARANCE OF VESUVIUS AFTER THE ERUPTION OF A.D. 79.

sides of the cone, and have flowed for long distances, but there has been no change in the position of the main vent.

Paroxysmal Eruptions.—The outburst of A.D. 79 affords a good example of the violent type of explosion which frequently succeeds a long period of quiescence. Several others have occurred within recent years, resulting in the partial or complete destruction of volcanic cones. Thus in the year 1772 the volcano of Papandayang, in Java, was reduced in height by 4,000 feet, and in 1822, in the eruption of Galoongoon, in the same island, a huge hollow was formed in the side of the mountain.

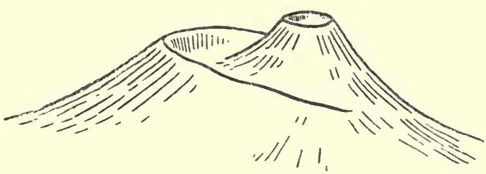


FIG. 76*c*.—DIAGRAMMATIC SKETCH OF THE APPEARANCE OF VESUVIUS IN RECENT TIMES.

Bandai-San, in Japan, had been quiescent for a thousand years, and in 1888, without much warning, it blew off its top and one side. Here again there was no lava and no fresh scoria, all the material thrown up consisting of fragments of the existing cone.

Krakatoa.—Somewhat similar in its effect was the well-known eruption of Krakatoa in 1883,[1] and this again had been quiescent for two hundred years.

[1] This eruption has been made the subject of a special report by a committee of th Royal Society (1888). The geological results have been admirably summa d by Professor Judd.

This island lies in the Straits of Sunda, between Java and Sumatra, directly on the line of the great fissure of the Old World. There is evidence [1] that exactly at this point that fissure is crossed at right angles by a minor one, running from Mount Pajung in Java to Mount Rajah-Bassá in Sumatra, and supporting a line of small volcanoes.

The Krakatoa group is a fragment of a great crater-ring, a basal wreck, the result of a great catastrophe of unknown date, slightly modified by later eruptions. Originally about twenty-five miles in circumference at sea-level, and probably 10,000 or 12,000 feet high, it was composed of enstatite-dacite materials resting on post-tertiary deposits.

The first great explosion formed a crater three or four miles in diameter, which was gradually filled up by eruptions of similar lava from small cones in its interior. The next phase consisted of eruptions of basalt from a lateral vent on the southern lip of the crater-ring;

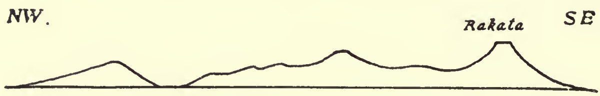


Fig. 77.—Form of Krakatoa in Historic Times.

After the formation of the lateral cone of Rakata and the growth of other cones in the crater.

this formed the cone of Rakata, which was 2,623 feet high. There was a gentle eruption from one or more of the smaller central cones in 1680, then quiescence for 200 years (see Fig. 77).

Premonitory earthquakes began in 1878 and gradually increased in violence. At last, on May 20, 1883, moderate activity began: noises were heard 100 miles away and steam rose from the central craters. This was a Strombolian phase, and increased in force up to August 26. On that day the volcano passed into the paroxysmal or Vesuvian stage. Loud detonations were heard, at first at intervals of ten minutes, but gradually with greater frequency, till they became almost continuous. Professor Judd thinks that during this period sea-water was gaining access to the heated magma and cooling the surface of it; he compares the general effect of this to fastening down the safety valve of a boiler while the fire continues undiminished. The natural consequence followed, and the eruption came to a climax in the form of four explosions of much greater magnitude. As a direct result of these the whole of the northern and lower part of the island disappeared, with the exception of one little patch of rock in the middle, about ten yards

[1] *Op. cit.*, p. 4, Fig. 1.

square, which is believed to have been originally a dyke or the plug of one of the smaller craters. Half of the cone of Rakata was also blown away, and the geological structure of its inner parts beautifully exposed. About two-thirds of the original area of the island disappeared, and over part of its former site a hollow was formed, in places 1,000 feet deep (Fig. 78). Two new islands were built up, possibly by parasitic cones, but they were soon worn down to sand-banks. The sea floor within a radius of ten or twelve miles is said to have been raised to an extent varying from 10 to 60 feet, but this was probably due to deposition of material and not to uplift.

Professor Judd gives the following explanation of the causes of the violent explosions in which the eruption culminated. The action in the vent during an eruption is exactly like that in a geyser. The lava is a mass of heated liquid from which large quantities of gas are being disengaged, and these carry up portions of the liquid in which

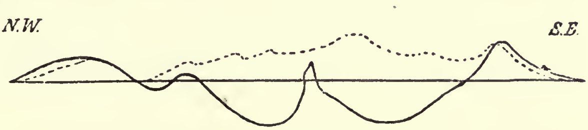


FIG. 78.—OUTLINE OF THE CRATER AS IT IS AT PRESENT.

The dotted line represents the portions blown away in the outburst of August 1883, and the change in form of the flanks of the mountain by the fall of ejected materials upon them.

they are entangled. The plugging of a geyser by throwing in turf or other rubbish causes an unusually violent explosion, since it prevents the escape of the steam until a larger quantity has accumulated, which suffices to overcome the extra pressure on the pipe ; so the interruption of regular ejections of the Strombolian type by the chilling of the surface of the lava by access of sea-water caused a check, and then a rally, of the pent-up force of the gas seeking to escape. It is sometimes stated that the water coming in contact with the heated magma was in this case the immediate cause of the great explosions, but it appears only to have acted indirectly in the above-mentioned way.

The secondary effects of these explosions in the way of air-waves, sound-waves, sea-waves, &c., were of unparalleled intensity, so far as existing records show, but, for full details, reference must be made to the memoir already cited.

Basal Wrecks and Calderas.—The general effect of these 'paroxysmal' eruptions is to produce a very great change in the form of the volcano : the upper part of the cone is destroyed, and the part left takes the form of an enormous circular cavity, surrounded by comparatively low walls. To such great explosion craters the name of *Caldera* is now commonly applied (Fig. 79). The whole structure is commonly spoken of as a 'basal wreck.' Such basal wrecks of volcanoes are common in many parts of the world: a good European example is the still feebly active volcano of Santorin, in the Greek Archipelago.

Calderas, however, are not always formed by explosion in the manner described above. If a great reservoir of molten lava, underlying a cone, should be drawn off through a side fissure instead of through the central vent, as sometimes happens, the upper part of the cone might fall in by its own weight. This process is known as *engulfment*. In this way Dutton and Diller accounted for the formation of Crater Lake, Oregon—a sheet of water five and a half miles in diameter, occupying a great circular hollow on the top of the Cascade Range. Their chief argument against the explosion theory is the absence from the surrounding country of any fragmentary material which could have formed the upper part of a cone of corresponding height.

The enormous craters of Hawaii are explained as due to slipping and foundering of slices from the walls during rise and fall of molten lava within the vent; but here the process is gradual and not catastrophic.

Fig. 79.—Section through a Hawaiian Volcano, with Caldera.

Etna.—When the centre of eruption does not remain in the same position throughout the whole history of a volcano, the structure becomes more complex: an instance of this shifting of the centre seems to have occurred in the case of Etna. On one side of the cone there is a great hollow or caldera known as the Val del Bove, and its origin is explained as follows. The first eruptions to occur were submarine and of Pliocene age. These built up a cone of moderate size. Presently the chief focus of eruption was shifted to some little distance, and built up a larger cone by which eventually the earlier one was completely buried. The latter vent after a time again became active, an explosion occurred, and a caldera was formed above it—the present Val del Bove. Later still the second vent, which constitutes the present crater of Etna, again became the outlet for the pent-up forces.

Etna is also remarkable for the large number of secondary cones and craters which occur on its flanks, for there are several hundred within a few miles of the summit. Such secondary vents are a very common feature of the larger volcanoes, and in many cases eruptions, and especially lava-flows, take place from them rather than from the main crater. It is often easier for the lava to find a passage through the sides of the cone instead of mounting to the top, and in some cases these outbreaks take place at a long distance from the summit: for instance, in 1840 a great flow of lava broke out on the flanks of

Tempest Anderson, photo.

(I) GRAND SARCOUI, FROM THE WEST: A DOMITIC PUY OF AUVERGNE.

Tempest Anderson, photo.

(II) THE PUYS OF AUVERGNE, FROM THE NORTH.

Kilauea at a distance of twenty-seven miles from the crater. These vents, filled with lava, form the dykes which are such a conspicuous feature of most dissected volcanoes.

Lava Cones.—So far we have dealt only with volcanoes in which fragmentary material is an important or even the only constituent, but examples are known of cones which consist entirely of lava. In this case the form will depend on the original character of the lava, and the state in which it is extruded. The chief factor is the degree of fluidity of the lava. At the ordinary temperature of emission, lavas with a high percentage of silica are very viscous, like treacle or tar, and these will evidently flow for short distances only. These acid lava-masses will tend to form rounded or dome-like forms, with steep slopes, and very often no crater is visible. This form is very conspicuous in the Puy de Sarcoui, in the Auvergne district (Plate XXVII); on the other hand, the giant volcanoes of Hawaii consist entirely of lava with a low silica percentage and a high proportion of metallic oxides: this becomes very mobile at a temperature at which an acid lava is highly viscous, and streams of it, in consequence, flow for very long distances and tend to spread themselves out in thin sheets. A cone built up of a succession of such streams will have a low angle of slope and a very wide base. Mauna Kea and Mauna Loa, in Hawaii, are both nearly 14,000 feet high and have an average slope of about 6°, so that they are nearly seventy miles in diameter. They also possess enormous craters; that of Mauna Loa has a circumference of about ten miles, and the crater of Kilauea is even larger.

The Soufrière and Montagne Pelée.—In the year 1902 there occurred in the West Indies eruptions showing some special features of a type which had not before been recorded. These eruptions were remarkable on account of the widespread destruction which they caused and the great loss of life which accompanied it. The chain of the Antilles is well known to be a volcanic region, and this vulcanicity occurs along the line of a fold of the Pacific type. In May 1902 there occurred two separate and distinct series of eruptions at the same time in the islands of St. Vincent and Martinique. The general phenomena were almost precisely similar in both cases, and the description of one will suffice. The eruptions in St. Vincent have been made the subject of a very detailed investigation by Drs. Flett and Anderson,[1] while those in Martinique have been similarly treated by the French geologists.

In the northern part of the island of St. Vincent is a volcano known as the Soufrière, which is about 4,000 feet high and eight miles in diameter at the base; its summit is occupied by a large crater, about a mile in diameter, and this, before the explosion, contained a lake, the water

[1] *Phil. Trans. Roy. Soc.*, vol. cc. A. p. 353.

of which smelt strongly of sulphuretted hydrogen, whence the name of the mountain. We may notice in passing that this gas is very characteristic of the West Indian volcanic region, and 'Soufrières' are abundant. The crater is partly surrounded by an outer ring of the Somma type, no doubt the 'basal wreck' of a larger cone. The volcano had been dormant for ninety years, except for the above-mentioned gaseous exhalations. After some premonitory warnings in the form of earthquakes during a period of twelve months, an eruptive phase began on May 6; on that day the crater-lake boiled and overflowed, but beyond this nothing very noteworthy occurred. Next day the eruption became much more violent, and soon reached a very remarkable climax. This consisted of the outburst of a great black cloud of gases and incandescent dust, which rushed down the side of the mountain, burning and destroying everything in its path. Within the area covered by the cloud all vegetation was destroyed, and all animals and human beings were killed, except those in tightly closed buildings. All descriptions of this eruption make special mention of the electrical phenomena which accompanied it, and a good deal of the destruction of buildings was apparently due to lightning.

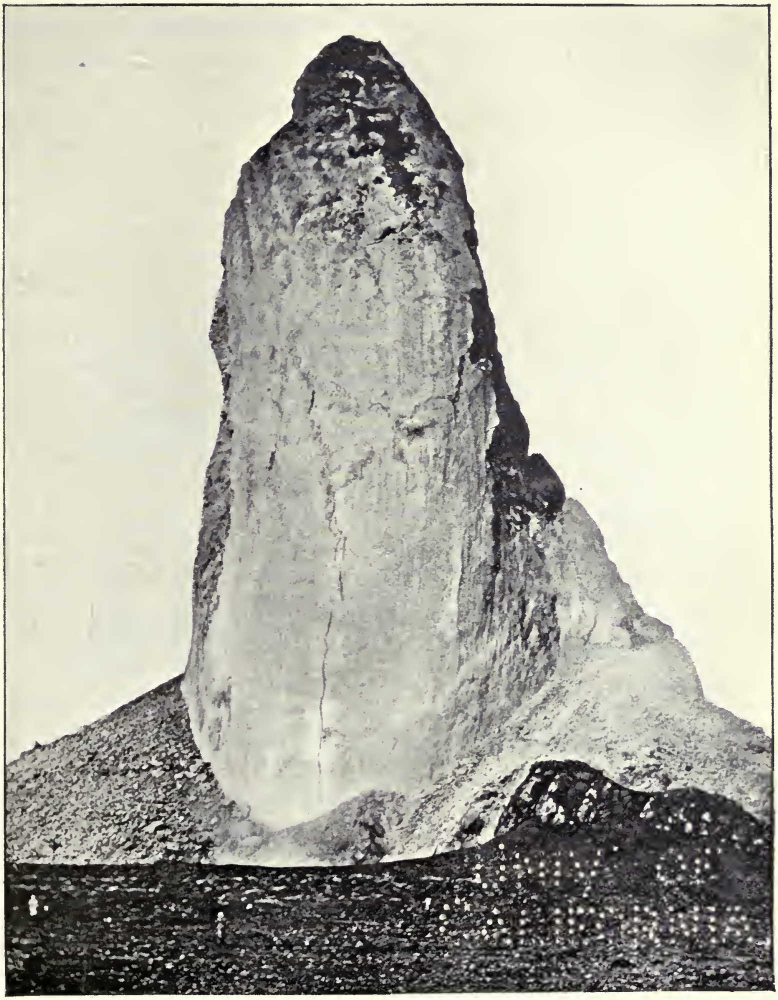
The general character of the eruption of Montagne Pelée,[1] in Martinique, was almost precisely similar; but here the loss of life was very much greater, since a similar cloud rolled straight down over the town of St. Pierre, which was practically blotted out of existence in a moment, and about 30,000 of the inhabitants perished.

This phenomenon repeated itself more than once, and one such eruption was witnessed in July 1902 by Drs. Flett and Anderson. They describe the cloud on this occasion as black and globular in appearance; it seemed to hang for a short time on the rim of the crater, and then rolled down the slope in heavy masses, looking, when it reached the sea, like the folds of a black curtain. It is clear that the source of energy of this cloud is its weight, and its movement is comparable to that of a heavy and mobile fluid, but somewhat complicated by an explosion at the moment of its emission.

The gases of the clouds were evidently very sulphurous, both sulphuretted hydrogen and sulphur dioxide being present in considerable amount, especially at the Soufrière. But the most abundant gas in both cases was undoubtedly steam. It has been suggested that the great loss of life might have been due to poisonous carbon gases due to bituminous deposits, but there appears to be no evidence in support of this. The gases are clearly those of the andesitic magma, which was not at a very high temperature, and when these gases were suddenly liberated they carried with them large quantities of solid matter in the

[1] Lacroix, *La Montagne Pelée et ses Éruptions.* Paris, 1904.

PLATE XXVIII



A. Lacroix, photo.

THE 'SPINE' OF MONTAGNE PELÉE.

form of red-hot dust or sand. Within the vent it was a molten magma, with many small crystals suspended in a liquid with enormous quantities of occluded steam. Relief of pressure on rising in the throat allowed the gases to expand, and the mass changed to a cloud of particles, mostly solid, mingled with the expanding gases.

The authors [1] previously cited summarise their conclusions as follows: 'Eruptions of the Peléan type are distinguished by the occurrence of one or more discharges of incandescent sand, which rush down the sides of the mountain in the form of a hot-sand avalanche, accompanied by a great black cloud of gases charged with hot dust, which sweeps over the country with a very high velocity, mowing down everything in its path.' Beyond the limits of the cloud no effects are produced, and there is otherwise nothing very special about these eruptions. In a Peléan eruption certain distinct stages may be identified—

1. Premonitory symptoms, without actual eruption: earthquakes, heating of water, &c.;
2. Preliminary stages of eruption, increasing in violence;
3. The climax, arriving suddenly: sand avalanche and cloud;
4. Concluding stages: gradual dying away of activity.

These eruptions have much in common with those of volcanoes of the ordinary explosive or Vesuvian type, to a sub-group of which they evidently belong.[2]

The 'Spine' of Montagne Pelée.—At a late stage in the history of the eruption of Montagne Pelée a strange phenomenon occurred.[3] An enormous spine or obelisk (Plate XXVIII), protruded itself from the top of the cone of eruption, and eventually reached a height of over 5,000 feet above sea-level, and some 700 feet or more above the summit of the cone. This spine consisted of solidified lava, and it is believed to be the plug of lava which had solidified in the pipe of the volcano at the end of the first phase of the eruption, and was subsequently slowly forced upwards by an increase of pressure from within. The spine very soon lost most of its height owing to ready denudation of the soft material.

Structure of Volcanoes.—A typical volcano consists of a more or less conical hill or mountain, called the cone, with a basin-shaped hollow at the top, called the crater. The crater is in direct communication with, and a continuation of, the pipe or vent which forms the channel of communication between the heated interior of the earth and the surface.

[1] *Op. cit.*, p. 499. [2] *Loc. cit.*, p. 500.
[3] Lacroix, *op. cit.*, chap. iii., and Plates I. *bis*, V. and VI.

The internal structure of the cone cannot usually be examined in detail in active volcanoes. It can be most effectively studied in the extinct examples which are common in many parts of the world among older rock-formations, and which have had their structure laid bare by denudation. They may be found in all stages of dissection—from nearly perfect cones with craters still remaining, down to mere stumps, of which the true nature is not at all obvious. Among the older strata, in many cases, all that is left is the plug of igneous rock which filled the original channel of eruption, that is, a 'neck': examples are abundant in Britain (see Plate XXIX). These show that the channel of eruption is usually cylindrical in form, and often passes through the stratified rocks without much disturbance, except that, owing to contraction on cooling of the material in the pipe, the surrounding strata are often dragged down towards the neck, so that for a short distance around all the dips are towards it (see Fig. 4, p. 12).

The cone may be built up of fragmental material only, of lava only, or more commonly of a mixture of the two; and the structure depends upon the composition. The simplest of all is a cinder cone, such as Mont Nuovo or many of those of Auvergne. The material, as it is ejected from the pipe, describes parabolic curves in the air, and, *cæteris paribus*, falls at a certain distance from the vent, according to its weight: at a certain distance from the orifice the deposit will reach a maximum, so that the material gradually accumulates in the form of a ring with slopes towards and away from the centre; on this, as the cone increases in height, new material will be deposited in inclined layers, dipping both outwards and inwards, a good deal of that which falls on the inner slopes rolling back into the vent, to be again ejected; and thus the cone is gradually built up with the peculiar quaquaversal dip which so sorely puzzled the earlier writers on volcanoes, and led to the long-since abandoned elevation crater hypothesis, which supposed that volcanoes were formed by upheaval; that they were, in fact, gigantic blisters on the earth's surface. The chief evidence in support of it was the structure of cones with their outward, and often steep, dip in all directions from the centre.

The addition of flows of lava to fragmental material does not essentially alter the type of structure. If the molten rock rises to the lip of the crater and overflows, it forms sheets intercalated with the ash and having the same angle of dip. In the case of large volcanoes, however, it is much more common for the lava to find its way out through cracks and fissures in the sides or near the base of the cone. These cracks and fissures must be regarded as branches of the main vent, and if they are on a fairly large scale they give rise to subsidiary cones and craters, which introduce great complications into the structure. These fissures may take the form of vertical cracks, and

Tempest Anderson, photo.

(I) ROCHER SAINT MICHEL, VELAY: A NECK OF VOLCANIC AGGLOMERATE.

Photo by H.M. Geological Survey

(II) NORTH BERWICK LAW, HADDINGTONSHIRE; A TRACHYTE PLUG.

when filled with solidified lava and exposed by denudation they form dykes which intersect the stratified material, and form a kind of strengthening network or skeleton for the cone. Dykes may extend in a radial form for long distances from centres of eruption, and although the rocks which fill them are technically intrusive they are essentially volcanic, and often approach much more closely to the lavas than to the intrusive rocks in their petrological characters.

Cones which are built up entirely of lava-flows vary much in structure according to the temperature and degree of viscosity of the lava. This question has already been dealt with in describing the lava-cones of Auvergne and Hawaii, and does not require further discussion. Enough has also been said as to the modifications produced by paroxysmal explosions, engulfments and other factors which tend to modify the form and destroy the symmetry of volcanic cones.

Dormant and Extinct Volcanoes.—Hitherto we have described chiefly volcanoes which are known to be in periodical activity, although the intervals which elapse between successive eruptions are sometimes very long. There are, however, many volcanoes of which no eruptions have been recorded within historic times, although there may be reason to believe that the volcanic forces are only temporarily quiescent. Such volcanoes are usually spoken of as dormant. Doubtless some of them will again show activity, and this perhaps of a violent nature, since many of the most destructive eruptions of recent years have taken place from volcanoes which had long been at rest. Again, there are numerous examples of volcanoes which have been quiet so long that they may be safely regarded as extinct. Such extinct volcanoes may either preserve their original form comparatively unchanged, like many of the cones and craters of Auvergne, some of which look as fresh as if they had been formed within the last hundred years, or they may have undergone so much denudation that their original character is masked, and can only be made out by close study. It may be noted in passing that a large part of our knowledge of the internal structure of volcanic cones is necessarily derived from an examination of extinct specimens which have been dissected by erosion and their inner parts laid bare. In particular, it is obviously impossible to study the vent or channel of eruption in living examples, while it is easy to do so if the cone and crater have been removed and the underlying parts exposed. It is only rarely, as in the case of the subsidiary cone of Rakata,[1] that we get a clean section formed by the blowing away of a part of the cone. No actual example of a crater now exists in the British Isles, but dissected volcanoes are abundant, and there is clear

[1] *Rep. Roy. Soc. on Krakatoa*, part ii., 1888.

evidence of the existence of vulcanicity on the largest scale within this area at many periods of its past history. Much will be said on this subject in subsequent chapters.

The Solfatara Stage.—In the intervals between their eruptions many volcanoes give off steam and various gases from their principal craters and minor openings, and during their decadence these are the only products emitted. They are of various kinds, and the nature of the gas given off serves as an indication of the degree of extinction of the volcano. A very good example of a volcano in this stage is afforded by the large crater known as the Solfatara in the Phlegraean Fields, near Naples. This may be now considered as approaching extinction, since the last recorded eruption occurred in A.D. 1198, when a flow of trachyte was given out. The crater is very wide, and is surrounded by walls which are only about 100 feet high. The floor is salt and marshy, with here and there a little pool of boiling water. At the foot of the wall on one side is a small opening called the Bocca, and from above this a jet of steam rises to a height of 6 or 7 yards.

Similar jets of steam, together with other gases, are very common in many dormant and decadent volcanoes. Such volcanoes are said to be in the Solfatara stage, which may be regarded as an indication of approaching extinction. Vents in the Solfatara stage are numerous in most of the great volcanic districts of the world, such as Iceland, Java, New Zealand and the Andes.

Products of Solfataric Eruptions.—Besides steam, such solfataric vents frequently give off other gases, such as hydrochloric acid, sulphur dioxide, sulphuretted hydrogen, ammonium chloride, carbon dioxide, &c. The evolution of these chemically active gases frequently leads to deposition of peculiar minerals round the openings, and causes great alteration of the surrounding rocks. Lavas and ashes are attacked by the acids and lose some of their constituents, so that the whole crumbles to a white powdery mass. This form of alteration can be well seen at Vulcano, and in many districts special names have been applied to rocks which are really nothing but ordinary lavas altered in this way by chemical action.

The gases given off in these circumstances have frequently been collected and examined, and the following classification has been proposed: those in which acid gases are dominant are called Solfataras, those which give off chiefly steam are Fumaroles, and those in which carbon dioxide is the principal product are Mofettes. These may be regarded as three successive stages.

This principle has been somewhat extended by St. Claire Deville, who finds that the kind of gas evolved depends on the temperature, which is, of course, also a measure of the degree of extinction. He distinguishes the following different types :—

1. Dry fumaroles, without steam; these give off, chiefly, anhydrous chlorides at a temperature above 350° C.

2. Acid fumaroles, hydrochloric acid and sulphur dioxide, with some steam, at temperatures above 100° C.

3. Alkaline fumaroles, giving off steam and ammonium chloride at about 100° C.

4. Cold fumaroles, nearly pure steam, below 100° C.

5. Mofettes, giving off carbon dioxide, nitrogen and oxygen at the temperature of the atmosphere.

In some of the Italian fumaroles, which are also known as *soffioni*, boric acid occurs as a special product, and its extraction has given rise to a considerable industry in Tuscany.

As an example of a mofette or source of carbon dioxide, we may mention the celebrated Grotto del Cane, near Lago d'Agnano, in the Phlegraean Fields,—a small cave with a floor sloping downwards away from the entrance, with an accumulation of carbon dioxide, which is heavier than air, at its end. The existence of this gas is demonstrated by lowering a dog into it: the animal rapidly becomes unconscious, but before life is extinct it is extracted and revived with cold water, to repeat the performance for the benefit of the next batch of tourists. A similar cave exists near Royat in Auvergne, and the so-called Upas Valley of Java appears to owe its deadly properties to a layer of the same gas at the bottom. It was probably something of this nature which gave rise to the old myth of Lake Avernus, over which it was said no bird could fly. Lago d'Averno certainly is a crater-lake, and it is possible that in the early days of man's habitation of Southern Italy it gave out gaseous exhalations of some kind.

Similar emanations of carbon dioxide are very common in the old volcanic districts of Central Germany and Bohemia, and must be regarded as the last traces of the once great activity which characterised that region in early Tertiary times. Closely related to them are the many varieties of effervescent and mineral springs, which are also found in many old volcanic districts.

Geysers and Mud-volcanoes.—In some parts of the world there occurs a peculiar type of eruption in which the principal product is not molten rock but water, which, however, is at a high temperature. Two types of these eruptions are usually distinguished: those in which clear water is the sole product are called *Geysers*, and those in which the water contains a considerable amount of solid matter in suspension are called *Mud-volcanoes*, but the two are essentially alike. The mud is derived from the surrounding rocks, and may be regarded as merely an accessory constituent, of no importance. Mud-volcanoes exist at Baku, on the Caspian, and on the Crimea, some of them showing distinct cones up to 250 feet high, with a crater at the top. The mud-volcanoes of Paterno, in Sicily, are of special interest, because they occur along the line of the great fissure which runs in a S.S.W.–N.N.E. direction through Etna and the Lipari group. The mud-volcanoes of Krafla, in Iceland, are also well known. They consist of boiling pools of thick black mud, the level of which rises and falls intermittently: they are simply very dirty geysers.

Geysers may be regarded as the paroxysmal phase of hot springs; at intervals they erupt, and throw a column of hot water and steam high in the air; then they remain quiescent for a certain interval of time, when the process is repeated.

The best-known examples of geysers occur in Iceland, the Yellowstone Park and New Zealand, all of which are regions of decadent volcanic activity. The volcanoes of the Yellowstone Park region are extinct, while those of the other two districts are probably approaching that stage. In its origin and mode of action a geyser is precisely similar to a volcano, and the resemblance goes so far that geysers even build up a cone and crater on a small scale from material suspended from solution, as will be explained subsequently.

One of the best examples is the Great Geyser of Iceland, which gives its name to a whole class. It lies in a plain north-west of Hekla, at the foot of Barnafell. Around the opening is a low cone, about 13 feet high and about 120 feet in diameter. At the top of this is a basin about 5 feet deep and 60 feet in diameter. In the middle of this basin is the opening of the pipe, which has a diameter of about 16 feet, with smooth cylindrical and vertical walls. This pipe and basin is ordinarily filled with still clear water at a temperature of from 75° to 90° C. At a depth of 100 feet in the pipe the temperature is about 130°, so that even close to the surface the water is considerably superheated. About every twenty-four hours an eruption occurs, and the water in the basin is thrown up into the air to a height of nearly 200 feet, together with great clouds of steam. The other geysers of Iceland and the districts named show similar phenomena, and do not need separate description.

The explanation of geyser eruptions is simple but of great importance, since it throws light on the origin of ordinary volcanic eruptions. We have seen that at a depth of only 100 feet the water is at a temperature much higher than its boiling-point under atmospheric pressure, hence at greater depths it must be under high pressure. As the temperature increases the vapour tension of the water also increases, till eventually a point is reached when the tension of the vapour exceeds the pressure due to the column of water above; the water at this point passes suddenly into steam, which, on expanding, raises the column, causing an overflow of water at the surface. This diminution of pressure allows the superheated water to flash into steam, which blows out the whole column and causes the eruption.

Classification of Volcanoes.—From the examples of volcanoes and their attendant phenomena which have been described above, it will be seen that a good deal of variation is exhibited. The differences are of two kinds: first of all, actual and fundamental structural variations, as will be seen by a comparison of the fissure-eruptions of the Snake River plains with gigantic cones like Etna or Cotopaxi; and in the second place, variations due to the fact that all volcanoes are not in the same stage of their life-history; some are embryonic, some in full activity, some decadent, and some dormant or extinct. The examples here described in some detail have been chosen so as to illustrate as much as possible these different phases and stages of vulcanicity. The following table exhibits in a greatly condensed form a summary of the results, it being of course understood that examples could be multiplied to any extent, and that no hard-and-fast lines can be drawn between the different groups, since all are connected by transitional instances:—

ACTIVE PHASE.

Linear Vents.

Fissure eruptions . . .	Cracks in the crust, from which lava flows without explosion.
Icelandic type . . .	Very similar to above, but with more explosive action.

Localised Vents.

Explosion pipes . . .	Circular vents, produced by single explosion. Ex. Maare of Eifel, Diamond-pipes of South Africa.
Fragmental cones, of single eruption.	Ex. Monte Nuovo.

Cones of repeated eruption—non-paroxysmal—

a. Fragmental material only. Ex. Fuji-San.
b. Fragmental material and lava. Ex. Stromboli, Andes.
c. Lava only. Ex. Kilauea, Hawaii; Puy Sarcoui, Auvergne.

Cones of repeated eruption—paroxysmal—

Cones of lava and fragmental material, often with calderas. Ex. Vesuvius, Etna, Krakatoa, Bandai-San, Soufrière.

STAGES OF DECADENCE.

a. Solfatara stage.
b. Fumarole stage.
c. Stage of geysers and mud-volcanoes.
d. Stage of hot springs.
e. Stage of effervescent springs and mofettes.

The Distribution of Volcanoes.—Volcanoes do not occur scattered at random over all parts of the earth's surface, but their distribution shows certain well-marked features. It has long been noticed that practically the whole of them occur within a comparatively short distance from the sea, or from some large sheet of water. The existence of some active volcanoes in the Thian-Shan Mountains in Central Asia has been asserted, and these would form an important exception to the rule, but the evidence seems to be of a very insufficient nature. A few extinct craters have, however, been observed on the plateau of Thibet, between the Lob-Nor and Kuen-Lun chains, and some of the East African volcanoes, such as Kilimanjaro and Kenia, are at a considerable distance from the sea. But the latter are situated on an important line of fracture, the Great Rift Valley, and close to the African Lakes, so that in this case the exception is apparent rather than real. So far as we know, the same rule applies to the volcanoes of the past, and indeed there is abundant evidence to show that many of the most important outbreaks of the earlier geological periods were either submarine or situated close to shore-lines, since abundant remains of sea-creatures are found embedded in their ashes and tuffs.

A detailed examination of the distribution in space of existing volcanoes, either active, dormant or recently extinct, reveals some interesting features. Besides being almost confined to the neighbourhood of the sea, they show a very well-marked tendency to arrange themselves in lines parallel to the shores of the continents, and in particular they form an almost complete girdle surrounding the Pacific Ocean, which is often spoken of as the 'Pacific Ring of Fire.' Starting from the north-west end of the island of Sumatra, a line of more or less active volcanoes can be traced through Java, the Moluccas, the Philippine Islands, Formosa, Japan, the Kurile Islands, Kamchatka, the Aleutian Islands and Alaska. In British North America and in the United States there are no active volcanoes, but we find plenty of evidence for their existence in a (geologically) very recent period. Some of the highest peaks of Western America still possess well-formed craters, which have undergone but little denudation. In Mexico and Central America active vents are again common, and the line is continued by the chain of great volcanic peaks of the Andes as far as the southern extremity of the continent, and is probably prolonged into the islands of the Antarctic. Thus the coast-line of the Pacific forms the great volcanic region of the globe, in comparison with which all others seem insignificant. The most salient fact which arises from a study of this distribution is the coincidence of these lines of vents with the curved arcs indicating the folded chains which bound the Pacific, a coincidence which is in entire harmony with the views already put forward as to the fundamental connexion between earth-movements and igneous activity.

Turning now to the Atlantic region, we find that volcanoes are much less abundant, and their distribution is less conspicuously regular. Active volcanoes are rare on the Atlantic seaboard, though more common in the oceanic islands. In some districts, however, extensive vulcanicity existed during geologically recent times. During the early part of the Tertiary period N.W. Europe was the scene of fissure-eruptions on a large scale, and the products of these eruptions form thick beds of basalt in many of the Arctic Islands, Iceland, the Faroes, the Inner Hebrides, and the north-east of Ireland. The modern volcanoes of Iceland must be regarded as the direct descendants of these Tertiary vents. The recently extinct craters of the Auvergne are situated at no great distance from the Atlantic. Most of the oceanic islands of the Eastern Atlantic are wholly of volcanic origin, and there are a few recently extinct or dormant craters on the west coast of Africa. As before mentioned, there is an important series of volcanoes and igneous rocks along the line of the Great Rift Valley, even so far north as Palestine.

The volcanoes of the Mediterranean region, and in particular those of the Tyrrhenian group, must be regarded as a survival of the volcanic activity which accompanied the great mountain-building movements of Tertiary times; and in many districts on both sides of the Alpine chain, using the term in its broadest sense, we find abundant relics of great Tertiary and post-Tertiary eruptions, particularly in Central Germany and Bohemia on the northern side of the chain, and in Hungary on the southern side.

Turning now to the western side of the great Atlantic basin, we find the distribution of volcanoes to be of striking simplicity. They are, with one conspicuous exception, entirely absent from the Atlantic coasts of the two Americas; but a line of volcanic vents follows the curved arc of the Antilles, which is the sole example of a folded chain of Pacific type forming part of the western boundary of the Atlantic.

The facts here briefly summarised as to the geographical distribution of volcanoes may be regarded as the expression of a general law, namely, that vulcanicity accompanies the Pacific type of coast-line, and is absent from one of the Atlantic type.

Causes of Volcanic Eruptions.—In recent years the generally accepted view of the cause of volcanic eruptions has been that they are due directly to pressures exerted by crust-movements. We have already seen how, as a result of the cooling and contraction of the globe as a whole, this crust is wrinkled up, folded and cracked, and often large segments of it are thrust over others. These movements result in the production of lines of weakness, and we have already pointed out that the distribution of volcanoes follows such lines. It seems natural, therefore, to assume that the cause of vulcanicity is directly due to the squeezing out of the liquid, or potentially liquid, interior of the globe by these movements of contraction. There are, however, considerable difficulties in the way of this simple explanation; for example, amongst others, the explosive nature of the majority of eruptions, and the constant repetition of eruptions from the same vent at very short intervals of time. If all eruptions were due to the opening of cracks through the solid crust to the molten magma within, we must necessarily suppose that such fissures are constantly being formed to enormous depths, since on the cessation of the eruption the existing crack would be plugged up by the cooling of the lava and so rendered useless for future occasions. This difficulty is only reduced, but not removed, by the supposition that eruptions arise, not from the central molten mass, but from local magma-basins, reservoirs of molten lava, within a solid crust; because it would still be necessary that these fissures should be kept open or filled with magma material below a certain comparatively small depth.

It is obvious that water plays a considerable part in volcanic phenomena, and especially in eruptions of an explosive type. The well-known distribution of volcanoes near the sea, and the occurrence of chlorides in their products, have led some writers to suppose that the simple access of sea-water to heated material is a sufficient explanation of all the facts. But many other gases and vapours are also abundant, and could not be derived from sea-water.

The following is the explanation given by Arrhenius.[1]

Heated magma lies everywhere at a certain depth below the sea floor, through which water penetrates by capillarity. Since this magma has a temperature much above 365° C., the critical temperature of water, the water which reaches it must be not liquid, but gaseous. Gaseous water above the critical temperature has much the same density as liquid water, and forces its way into the magma in spite of the much greater pressure of the magma column, which in a volcanic vent must at least reach sea-level, if an eruption is to occur.

The sea floor with its capillaries acts like a semi-permeable membrane, with pores sufficiently large to admit liquid or gaseous water, but not the complex molecules of the magma constituents; consequently, great osmotic pressure is set up in the magma. Water continues to be taken up till its vapour pressure is as great as the weight of the overlying magma-column. By this means the magma becomes saturated with water, and increases in volume by nearly that of the water absorbed. This causes it to rise in the pipe, when another factor comes into play. At ordinary temperatures water is an extremely weak acid, about 100 times weaker than silicic acid. But on raising the temperature and pressure its properties change. Silicic acid, on the other hand, does not change its strength much. From existing data it can be calculated that at 300° C., water and silicic acid are about equal in strength; at 1,000° C. water is 80 times as strong; and at 2,000° C. 300 times as strong as silicic acid.

Thus at 2,000° C. or thereabouts water penetrates into magma and

[1] *Geol. Fören. i Stockholm Förh.* xxii., 1900, p. 395; Summary in *Geol. Mag*, 1907, p. 173.

decomposes the silicates. But as the magma rises in the pipe and cools, the reverse process sets in and water is again set free. The pressure of the water-vapour rises, notwithstanding the falling temperature; and if the watery layer is sufficiently near the surface, and therefore under sufficiently low external pressure, some of it will pass into steam with explosive violence.

According to this theory, a volcano acts just like a geyser. At great depths the water in the magma is under higher pressure than the maximum tension of its vapour, and no explosion is possible. When the magma enters the pipe, or when the pressure is relieved by movements of the crust, there comes a time when, by separation of the water from the magma, its vapour tension exceeds the external pressure, and an explosion occurs, blowing a passage for the steam to the surface. These explosions continue until so much steam has been lost that the vapour tension of the remainder is insufficient to overcome the external pressure, and a state of quiescence ensues until sufficient water has again penetrated to the magma to start the process anew.

This theory of vulcanicity, it may easily be seen, is in no way inconsistent with the idea of the dependence of igneous activity on crust-movements, of which it may be regarded as an amplification, since it only deals with the physics of the actual eruptive processes, and explains why continued eruptions may take place along any given line of weakness. It is, however, insufficient to account for the actual formation of the line of weakness, and this is most easily explained by contraction and crumpling of the earth's crust, leading to tangential stresses, folds and fissures.

It is possible that some cases of quiet out-wellings of lava, for example fissure-eruptions, may be simple movements of liquids under the laws of hydrodynamics; it is supposed that fissure-eruptions occur in regions of tension, where blocks of the crust are settling down by their own weight into the molten magma below. In most cases, however, we must regard the crust-movements as the ultimate cause, and the explosive action of high-pressure steam, as above suggested, the proximate one.

Cause of Intrusions.—It has been already pointed out that intrusions of igneous magma which cool and solidify below the surface cannot logically be separated from volcanic phenomena: both are manifestations of the same forces acting under different conditions, and therefore leading to somewhat different results. But both sets of phenomena are essentially the same, and the two types of rock are sometimes in visible connexion, though this is only rarely the case.

The fissures formed by crust-movements need not necessarily reach the surface, but may be confined to the lower layers of the crust; the magma will tend to squeeze itself along these planes or to fill up any hollows which may be formed, and, as Suess points out, the intrusion of a large mass of igneous rock can only take place when a hollow is previously formed for its reception.

There are many intrusions, either small in size or cooled under a thin covering of rock, which are petrographically lavas, although intrusive in their manner of occurrence. And to carry the argument further still, the dykes and sheets of lava which break through volcanic cones during eruptions are also in part intrusive since they cut pre-existing rocks, although they pass laterally into lava-flows of the ordinary extrusive. Hence it is impossible to draw any hard-and-fast line between the two groups.

Origin of Igneous Activity in general.—To sum up, we see that the movements of molten magma which are comprised under the general term of igneous activity are brought about by two sets of causes—

1. The movements of the earth's crust, which determine the direction of flow of the material;
2. The chemical and physical properties of highly heated substances, especially water, which form the actual motive power.

Therefore, according to this view, vulcanicity in all its forms is merely a secondary effect of the greater class of phenomena dependent on the cooling and contraction of the globe as a whole.

CHAPTER XIII

THE IGNEOUS ROCKS

Intrusive Rocks

Under this heading are included all those rock-masses formed by the solidification of molten material injected into the earth's crust. Hence the form of the intrusion is determined chiefly by two factors, viz. the degree of fluidity of the magma, and the position of the dominant planes of weakness in the rocks into which it is intruded. The distinction between the intrusive and extrusive rocks is a somewhat arbitrary one, since intrusive masses can often be shown to pass into lava-flows, which have been poured out on the surface, and lava-flows must obviously be connected with a subterranean reservoir of molten rock, which is essentially an intrusion. But the division is a convenient one in practice, and there are certain well-marked physical and structural differences between intrusive and extrusive rocks as a whole.

The Degree of Fluidity of the Magma.—The form of an extrusive flow is determined chiefly by the fluidity of the magma, since, other things being equal, a less viscous magma will flow farther, and form a thinner sheet than a more viscous one. The degree of fluidity depends partly on the temperature and partly on the chemical composition of the magma ; a basic magma forms a highly mobile liquid at a temperature at which an acid one is still very viscous. The most viscous magmas of all appear to be certain sub-acid or intermediate types, rich in alkalies, especially the trachytes and phonolites.

In respect of the intrusive rocks similar considerations apply. A liquid magma possesses a much greater power of penetrating along planes of weakness than a viscous one, and in consequence tends to spread itself out in thin sheets along the bedding planes of the strata, while a viscous magma has little penetrating power, but arches up the strata into a dome-like form over a comparatively small area.

The Influence of Rock-structure on the Form of Intrusions.—Since the form of intrusive masses is to a great extent determined by the arrangement of the dominant planes of weakness in the rocks into which they are intruded, it is evident that the structure of the latter is an important factor in the case. The structures of rocks from this point of view are chiefly dependent on the type of earth-movement to which they have been subjected. As we have already seen, in regions affected by continent-building and plateau-building movements, the rocks remain horizontal or but slightly inclined over large areas, while in regions of mountain-building movements they are often highly folded, contorted and fractured. It is possible to distinguish two types of intrusions corresponding to these differences of structure, which may be referred to as intrusions in unfolded and folded areas respectively.

Intrusions in Unfolded Areas.—The best examples of this class of intrusions are found in the Western States of America, in Colorado, Utah and Wyoming, in connexion with the great plateaux of that region. In this case, according to American authorities, the form of the intrusion is closely connected with the degree of fluidity of the magma. The following types are recognised by Russell[1]: Sheets, Laccoliths, Plutonic Plugs, and Subtuberant Mountains.

Sheets or Sills.—In this form of intrusion the magma has penetrated for great distances along the horizontal or inclined bedding planes, so that the lateral extent of the mass is great as compared with its thickness. The typical example selected by Russell is the 'Palisade Trap' of New York State, which occurs over an area of at least 6,000 square miles, and attains a maximum thickness of 850 feet. A good instance of a similar sheet is found in the Great Whin Sill of the north of England, which extends into five counties: Northumberland, Durham, Yorkshire, Westmorland and Cumberland. It is intrusive into the Lower Carboniferous series over an area of at least 1,500 square miles: how far it extends to the eastward is unknown. Its maximum thickness is about 150 feet. It does not occur at one horizon throughout, but is distinctly transgressive (see Fig. 3, p. 11). So far as is known, all of these widely extended thin sheets consist of basic or sub-basic rocks, derived from a magma of a high degree of fluidity, which is able to penetrate to great distances along the bedding planes of the rock into which it is intruded.

Laccoliths.—Many of the intrusions in the plateau region of America and elsewhere take a form to which the name of laccolith has been given.[2] In this case the intrusive rock has arched up the overlying strata into the form of a dome, and has itself assumed somewhat the shape of a flat loaf or tea-cake (Fig. 80). In some cases, however, the form is more complex than this, since the main mass gives off more or less irregular offshoots, or apophyses, into the surrounding strata (Fig. 1, p. 10).

[1] *Journ. Geol.*, vol. iv., 1896, p. 176.

[2] Gilbert, *Geology of the Henry Mountains*, p. 19.

PLATE XXX

Photo by H.M. Geological Survey.

(I) SILL OF COLUMNAR QUARTZ-PORPHYRY, WITH A SMALL BASALT SILL AND BEDS OF TRIASSIC SANDSTONE AND SHALE BELOW. A RAISED BEACH IN THE FOREGROUND. DRUMADOON, ISLE OF ARRAN.

Photo by H.M. Geological Survey.

(II) TRAPRAIN LAW, FROM THE SOUTH. A PHONOLITE LACCOLITH OF CALCIFEROUS SANDSTONE AGE.

A laccolith often passes at its margin into a sheet or sill, and frequently smaller subsidiary laccoliths are found to be be intruded in the region where the bending of the strata around the main laccolith is most pronounced (see Fig. 80).

It appears probable that in these simple cases the whole mass of the igneous rock has been intruded at one time, but instances are known of intrusions which appear to consist of a series of laccoliths one above the

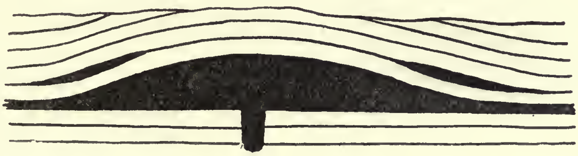


Fig. 80.—Laccolith passing laterally into a Sill, with Minor Laccoliths.

other, the so-called 'cedar-tree' laccolith (Fig. 81). Here it is probable that each projecting portion represents a separate injection of molten magma, and that the whole is due to a succession of intrusions from one common source.

The classical examples of laccoliths are those described by Gilbert in his 'Geology of the Henry Mountains,' but a similar structure has since been recognised in many other localities. The great gabbro and

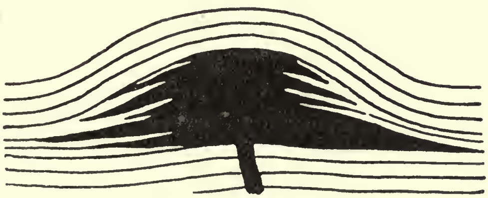


Fig. 81.—'Cedar Tree' Laccolith.

granite intrusions of the Cuillin Hills and Red Hills in Skye are of this nature.[1] In most cases the channels through which the magma rose have not been exposed by denudation and their existence is a matter of inference.

Bysmaliths or Plutonic Plugs.—In the Black Hills of Dakota and some other localities in Western America a peculiar type of intrusion has been described, under the name of Bysmalith or Plutonic Plug. These do not seem to differ in any essential respect from ordinary laccoliths, but they appear to consist of rocks of a still higher degree of viscosity, so

[1] Harker, 'The Tertiary Igneous Rocks of Skye,' *Mem. Geol. Survey*, 1904, p. 83.

that their thickness is greater in comparison with their horizontal extent. One of the best examples is Mt. Holmes, in the Yellowstone Park, described by Iddings[1] (see Fig. 82). Here the amount of vertical displacement produced by the intrusion is so great that the overlying rocks have been fractured to a certain extent around the circumference of the igneous mass. The distance to which the plug extends downwards is unknown.

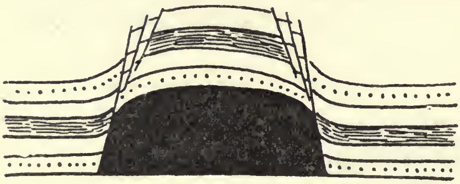


FIG. 82.—BYSMALITH.

A group of intrusions in the Black Hills of Dakota have been described by Russell[2] as belonging to this type. It must be stated, however, that his interpretation of the phenomena observed is questioned by Iddings,[3] who regards the intrusive masses as the remains of partially denuded laccoliths.

Minor Intrusions : Dykes and Sills.—Minor intrusions chiefly take the form of thin sheets of rock, which are either injected along the bedding planes, forming sills (Fig. 83), differing only in size from the sheets or sills above described, or else they cut across the stratification, when they are spoken of as dykes (Fig. 84 and Plate XXXI). The distribution of dykes is generally connected with the intrusion of large plutonic masses, or else they are subsidiary effects of crust-movements on a large scale. In the first case they tend to possess a radial arrangement around the central intruson, while in the second case they show parallelism over large areas. Such systems of parallel dykes have often served as the channels of fissure-eruptions (see p. 201).

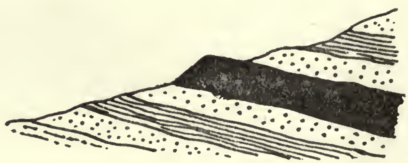


FIG. 83.—INTRUSIVE SILL.

The Tertiary Igneous Rocks of N.W. Europe.—The connexion between crust-movements of the plateau type and igneous activity generally has been worked out in much detail by Mr. Harker,[4] in Skye and the region near it. Two parallel series of events have been here recognised, which to a certain extent alternated with one another. These are, respectively, the regional, which affected the whole area,

[1] Iddings, *Journ. Geol.*, vol. vi., 1898, p. 704.

[2] Russell, *Journ. Geol.*, vol. iv., 1896, p. 23.

[3] Iddings, *loc. cit.*, p. 706.

[4] Harker, *Trans. Edin. Geol. Soc.*, vol. viii., 1905, p. 344; *Geol. Mag.*, 1901, p. 506; 'The Tertiary Igneous Rocks of Skye,' *Mem. Geol. Surv.*, 1904.

Photo by H.M. Geological Survey.

TERTIARY BASALT DYKE CUTTING TRIASSIC SANDSTONE. PORT A LEACACH, SOUTH-EAST COAST OF ARRAN. THE DYKE IS TWO FEET BROAD.

PLATE XXXII

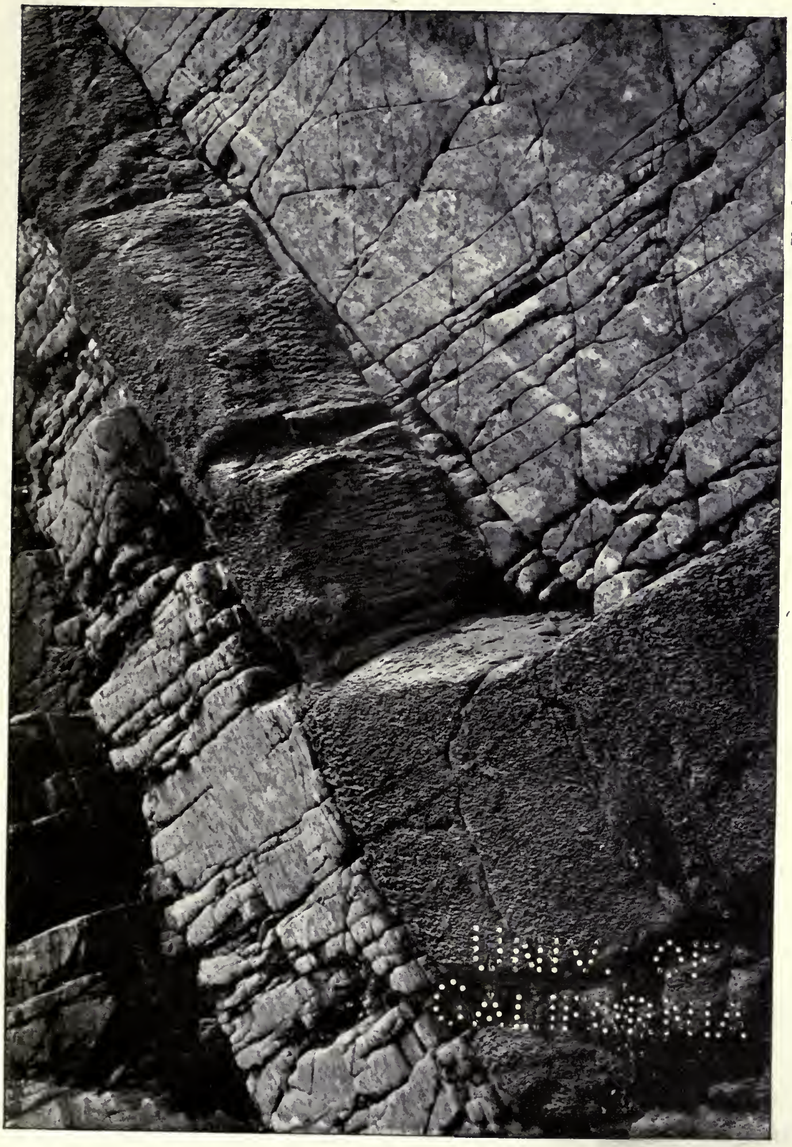


Photo by H.M. Geological Survey.

CLEAVED LAMPROPHYRE DYKE IN GRITS. NORTH SIDE OF KILCHIARAR BAY, ISLAY.

and the local, which were closely connected with certain special foci of activity. This classification applies to both igneous rocks and crust-movements. To the regional category belong a vast outpouring of basalt, due to fissure-eruptions (see p. 202), a great group of dolerite sills, and many groups of basic dykes, which extend over an enormous area. The crust-movements to which these rocks stand related were of the plateau-building type, and possibly connected with the formation of the Atlantic depression. They gave rise to an extensive system of faults, which divided the country into blocks. To the local category belong the occasional explosive volcanic outbursts, the large plutonic laccoliths, and certain groups of sills and dykes immediately surrounding the laccoliths. These outbursts accompanied movements by which the strata were to some extent folded, and the directions of these folds often coincide with older lines of disturbance marked out long before by previous movements.

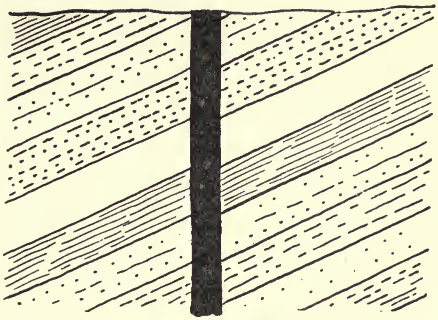


Fig. 84.—Dyke.

Intrusions in Folded Areas.—The forms assumed by masses of intrusive igneous rock in folded regions are naturally less simple and less regular than those just described, since the arrangement of the dominant planes of weakness varies in every case according to local circumstances. As a consequence of this the nomenclature of this group of intrusions is in a somewhat confused state, and no definite classification can here be given, as in the case of unfolded areas. According to the various forms assumed, such irregular intrusive masses are described as bosses, stocks, necks, sheets, dykes and veins. In most cases the definition of these terms is not very precise. In a folded region molten magma will find its way along the crests and troughs of anticlines and synclines, where the strata are stretched and weakened, avoiding the middle limbs where compression occurs. These long narrow intrusions are called by Mr. Harker *phacolites* (more correctly *phacoliths*) (see Fig. 85). Although frequently employed, the term

Fig. 85.—Phacoliths. (After Harker.)

laccolith should be avoided as a description of intrusions of this type.

The term *Stock* is used by some writers in a sense almost synonymous with boss. It is defined as an intrusive mass of irregular cross-section, and often of large dimensions, which cuts across surrounding rocks ; it forms an intermediate stage between a boss and a dyke.

The term *Neck* is commonly employed to express the plug of igneous rock filling up the vent or channel, of an ancient volcano, which has been revealed by denudation. Such necks are usually more or less circular in ground-plan and often give off apophyses in the form of sills and dykes. Many of the larger masses of this type are composed of plutonic rocks. A good example of such a neck on a large scale is afforded by the Shap Granite, which forms an irregular oval, having a longer diameter of a little under two miles.[1] Rock masses of a very similar kind are also well developed in Caernarvonshire, and these appear to occupy the vents of volcanoes of Ordovician age.[2]

The sheets, sills and dykes which occur in folded areas do not differ in any essential respect from those previously described in unfolded areas, except that they naturally do not generally possess so great a lateral extension. Owing to the complexity of the prevailing structures the terms used cannot be very strictly defined, but, generally speaking, intrusive sheets and masses of rock parallel to the bedding planes are called sills, whereas those which cut across the bedding planes are dykes. Originally, most sills are more or less horizontal, whereas dykes approach the vertical, but as a result of subsequent movements they may come to be inclined in any position. Besides the foregoing, there are often to be found masses of igneous rock of various sizes which cannot be classified under any definite heading, but are of entirely irregular form. These are mostly of small dimensions.

Composite Dykes and Sills.—The igneous material composing intrusive masses is not always injected all at one time ; in many cases it is clear that a given mass is the product of two or more successive intrusions. Reference has already been made to the possibility of such an occurrence in the case of the so-called 'cedar-tree laccoliths' (see Fig. 81). Here the successive injections are uniform in character. In other instances, however, there are to be found intrusions made up of successive injections of rock of varying character. It is not uncommon, for example, to find a large sill made up of two, three, or more layers of an acid and a basic rock alternately.[2] A similar structure is also observed in dykes, but the number of separate intrusions is rarely so great in these as in sills. Composite sills and dykes are abundant among the

[1] Harker and Marr, *Q.J.G.S.*, vol. xlvii., 1891, p. 266.

[2] Harker. *The Bala Volcanic Series of Caernarvonshire:* Sedgwick Essay for 1888.

tertiary igneous rocks of the Western Isles of Scotland, and are a characteristic feature of this petrographical province.[1]

The Composition and Classification of Igneous Rocks. Petrology.—In the introductory chapter a short account was given of the mineral composition of the principal igneous and sedimentary rocks, but it is now necessary to consider in somewhat more detail the chemical composition of the molten material before solidification, and the character of the rock produced by such solidification under different conditions. This, in its full development, constitutes the subject of *Petrology*, which is one of the major subdivisions of geology. Petrography is the branch of petrology which deals with the detailed classification and description of all known rocks, of whatever origin; this subject is too large to be discussed here. Reference must be made for this to some of the special text-books.[2] Space will only allow of the discussion of the principles underlying the ordinary classification, and some of the more important physical and chemical problems which are involved.

The Magma.—The term *magma* is used in recent petrological writings to express the molten material from which igneous rocks are formed. The term can therefore be applied without restriction to the raw material of igneous rocks of all kinds, whether intrusive or extrusive, and all igneous rocks must be regarded as the products of the consolidation of magma of varying composition under varying conditions. According to the recent views of Vogt, Doelter, Brögger, Harker and others, a magma is to be regarded as a solution, and obeying the laws of solutions. In the main this statement appears to be true, but one important qualification must be made. Many of the Laws of Solution, so far as at present known, are chiefly based on the investigation of dilute solutions, whereas rock-magmas must be highly concentrated or saturated. Consequently, important deviations from these so-called laws may possibly occur. In so far, however, as we are acquainted with the laws governing saturated solutions, and in particular the equilibrium of heterogeneous masses, as worked out by Willard Gibbs, Bakhuis Roozeboom and others, the results obtained by the experimental study of fused rock masses appear to be in harmony with them.

The Chemical Constituents of Rock Magmas.—It is probable that all, or nearly all, the known elements are found in igneous rocks, but many of them are exceedingly rare, and only a small number are of any importance. The elements which occur in large amount in igneous rocks, or

[1] Harker, 'Tertiary Igneous Rocks of Skye,' *Mem. Geol. Surv.*, 1904, p. 197. In this work a summary is given of the literature relating to the subject.

[2] Harker, *Petrology for Students*, 4th ed., 1908; Rosenbusch, *Elemente der Gesteinslehre*, 3rd ed., 1910; Hatch, *Text-book of Petrology*, 1909, &c.

what may be called the normal constituents of the magma, are the following: oxygen, silicon, aluminium, iron, calcium, magnesium, sodium, and potassium: these form about 99 per cent. of the whole, according to the most trustworthy estimates, obtained by combining a great number of analyses of rocks of all kinds.[1] The following elements are also of almost universal occurrence in small quantities: titanium, hydrogen, carbon, phosphorus, manganese and sulphur. These together form about 0·9 per cent., while the remaining 0·1 per cent. includes the rare constituents.

Instead of regarding the elements as the constituents of the magma, it is found more convenient in practice to consider them as combined with oxygen in the form of oxides: the constituents of the magma can then be arranged in natural groups, characterised by analogous chemical and physical properties; that is to say, the members of each group are isomorphous with one another (except Group V). Such an arrangement is shown in the following table:—

I. Silica, SiO_2.
II. Alumina, Al_2O_3; ferric oxide, Fe_2O_3.
III. Magnesia, MgO; ferrous oxide, FeO; lime, CaO.
IV. Potash, K_2O; soda, Na_2O; water, H_2O.
V. The accessory constituents, titanium dioxide, TiO_2; phosphorus pentoxide, P_2O_5; carbon dioxide, CO_2, &c.

It will be observed that in this table iron occurs twice, as the ferrous and ferric oxide; this separation is abundantly justified on chemical grounds, since each of the two oxides forms a series of well-defined compounds, having different physical properties.

From this point of view a fused rock-magma must be regarded as a mutual solution of all or any of these constituents. Consequently, the number of components of such a system is very large, and the whole phenomenon becomes very complex. For practical purposes the accessory constituents (Group V) may usually be disregarded, but even then the solution may contain as many as nine different oxides. To minimise this difficulty, Vogt has proposed to take as the components of the system those minerals which will eventually crystallise out of it, but even in this case the number is necessarily large. Another complication is also introduced by the fact that under certain conditions the whole or part may not form crystalline minerals of definite composition, but may solidify as a homogeneous, amorphous mass, a *glass*. Since such a non-crystalline mass may vary indefinitely in its composition, and is of uniform composition throughout, the chemical composition of such a rock is all we have to rely on in its classification. Crystalline rocks, on the other hand, need not be homogeneous: their composition may

[1] Clarke, 'Analyses of Rocks,' Bulletin 168, *U.S. Geol. Survey*, 1900, p. 15.

vary at different points. This is equivalent to saying that they are composed of an aggregate of crystals of different minerals. Here, then, besides the chemical composition, we require to know also the nature of the minerals present, and the proportion in which each occurs, before we can assign the rock to its proper place in the scheme of classification. Attempts have been made in America[1] to devise a classification based entirely on chemical considerations, but this has not yet found acceptance in this country.

Chemical Characters of Rock Constituents and Magmas.—In the great majority of cases silica is the most abundant constituent, and it very commonly exceeds in amount all the others taken together. The range of silica content in normal rocks is from about 40 to 80 per cent. : in only a few exceptional cases is it above or below these figures. Nearly all the important rock-forming minerals are silicates, or compounds of silica with one or more metallic oxides. In these compounds silica may be regarded as playing the part of an acid, while the metallic oxides act as bases. Hence rocks rich in silica are spoken of as *acid*, and those poor in silica but rich in metallic oxides as *basic*. It will thus be seen that in many respects silica is the most important constituent of a magma, and the proportion in which it is present is of great weight in classification, since the manner in which the basic oxides combine to form minerals is to a great degree controlled by the amount of silica present.

It has been found convenient to represent the chemical composition of the igneous rocks, and the relationships of the different groups, by means of a diagram, as follows : for abscissæ we take the percentage of silica as the dominant constituent, and for ordinates the sum of the percentages of potash and soda. It is obvious that any other constituent or group of constituents could be used in a similar way, but the alkalies are found to give the best results. In such a diagram the composition of any rock, plotted from its analysis, is represented by a point. When a sufficiently large number of analyses of rocks from all parts of the world are plotted in this way, some interesting facts become apparent : the points tend to arrange themselves into two linear groups, having a peculiar arrangement ; these linear groups of points can be generalised by drawing curves through them, and these two curves are convex upwards, but one much more so than the other (see Fig. 86). We thus obtain two curves approximating at the ends and diverging most widely in the middle. The first series is now commonly spoken of as the alkali series, and the second as the calc-alkali or sub-alkali series. For this purpose potash and soda alone are considered to be alkalies, whereas

[1] Cross, Iddings, Pirsson and Washington, *Quantitative Classification of Igneous Rocks*, Chicago, 1903 ; and summary in *Journ. Geol.*, 1902, p. 555.

lime is not; and indeed it may be said that lime is, in a petrological sense, in opposition to the potash-soda group, since lime characterises the sub-alkaline series.

Petrographical Provinces.—When a sufficiently large number of analyses have been made of the rocks of any given area, it is frequently found that even though there may be a wide range in composition, and especially in silica percentages, nevertheless certain chemical peculiarities run through the whole series. It is also found that the rocks of one area differ in some special manner from the rocks of some other area or areas. Thus, for example, the vast majority of the igneous rocks of Britain belong to the group described in the last section as sub-alkaline, poor in alkalies and rich in lime. The rocks of the New England States,

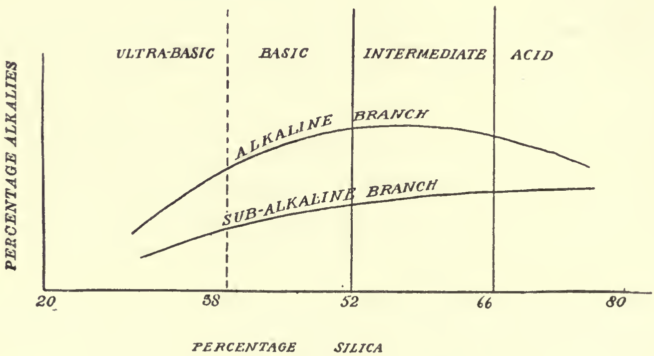


FIG. 86.—DIAGRAM OF IGNEOUS MAGMAS.

on the other hand, are distinctly alkaline, being characterised by a high alkali-content, and especially by the abundance of soda; other regions where alkali rocks are specially well developed are Southern Norway, Finland, Portugal and Brazil; while good examples of sub-alkaline regions are Hungary and the Pacific slope of the American continent. Any region which is thus marked off by special peculiarities is conveniently known as a *petrographical province.*

The occurrence of chemical peculiarities running through all or nearly all the igneous rocks of a province shows that they are not brought together by chance, but that there must be some real relationship between the different types: that is to say, all the rocks of a petrographical province may be referred to some common origin.

Igneous Complexes.—The same conception may also be extended to groups of rocks on a much smaller scale than those referred to in the last section. It is frequently found, when any igneous mass is examined in detail, that there are chemical and mineralogical peculiarities running through a number of rock types composing the whole; in particular there are often to be found in association a variety of rocks differing from one another in detail, and especially in silica percentage, but still resembling one another strongly in other points; such peculiarities may be either chemical, as in the case of petrographical provinces, or mineralogical; that is to say the different rocks possess in common one or more peculiar minerals, or associations of minerals, which serve to indicate relationship, or derivation from a common source. A set of mutually related rocks of this kind, occurring within a comparatively small area, is usually spoken of as forming an *igneous complex.* It is not practicable at this stage to give any actual examples of this kind, since to do so would involve an acquaintance with the detailed classification of the igneous rocks generally, but many such are known in Britain and elsewhere.

Solidification of the Magma.—The solidification of a molten rock-magma, whether intrusive or extrusive, must take place in accordance with the physical laws which govern the behaviour of solutions. As has been already pointed out, there are three distinct cases to consider: (1) the whole may solidify as a homogeneous mass, a *glass* in the petrographical sense; (2) it may solidify as an aggregate of crystalline minerals; (3) the resulting rock may consist partly of crystals and partly of glass. These differences correspond to the different conditions under which solidification takes place. Slow cooling favours crystallisation, whereas rapid cooling leads to formation of glass. Now the conditions which produce slow cooling are especially (1) the existence of a large body of molten magma, (2) a thick covering of rock above it. Consequently, large deep-seated masses are always wholly crystalline and generally coarse in texture. Lava-flows, on the other hand, are usually comparatively thin, so that they lose heat quickly, and they are commonly poured out on the surface of the ground. Hence lavas have a strong tendency to solidify as glass, and the same applies to small masses intruded under a thin cover of rock. But here another factor comes into play, since magmas of different chemical composition show varying powers of crystallisation. A high percentage of silica favours formation of glass, consequently many acid lavas are glassy, whereas basic rocks are rarely glassy to any great extent; as a rule such basic rock-masses only possess a thin selvage of glass on the surface, or on the edges of small dykes and sills, chilled by contact with cold walls. Large deep-seated masses of any kind often possess a marginal layer of finer texture, but they heat up the surrounding rocks to such an extent that formation of glass is prevented.

Porphyritic Structure.—In some crystalline rocks the texture is fairly uniform, so that it is apparent that crystallisation has been a continuous process carried on under uniform conditions without noticeable interruption. But in other cases the rock shows comparatively larger and well-formed crystals of one or more minerals embedded in a *ground-mass* or base of much finer texture, or even glassy. This constitutes what is known as the *porphyritic* structure. The explanation usually given is that this is due to crystallisation or solidification in two stages, under different conditions. The simplest case is where the magma at the time of intrusion or extrusion contained ready-formed crystals enclosed in the molten liquid. The liquid part then solidified quickly as a finely crystalline or glassy mass, enclosing the porphyritic crystals or phenocrysts. This explanation is supported by the fact that these phenocrysts have often undergone a certain amount of corrosion, or *resorption*, having their angles rounded off, and showing signs of a partial re-solution. This is probably due to change of conditions, and especially to relief of pressure, during the transit of the magma to its present position. Porphyritic structure is specially characteristic of lavas and the smaller intrusive masses, and is more rare in large and deep-seated intrusions. Still, it does occur even in these, and the porphyritic structure in this case has been said [1] not necessarily to imply any change of conditions during cooling, except the natural and gradual loss of heat which must always occur. It is suggested that during crystallisation of a magma a number of centres of crystallisation are set up at considerable distances apart, and the crystals thus started continue to grow up to a certain point, when the viscosity may become too great for free diffusion, necessitating the setting up of fresh centres of crystallisation at a smaller distance. This probably applies to the cases where the same mineral occurs in phenocrysts and in the ground-mass, but it is inapplicable where the constituents are different. According to Ostwald, in a saturated solution large crystals tend to grow at the expense of smaller ones, and this may occur also in magmas cooling with extreme slowness, under a very thick cover. Quite recently the opinion has gained ground that in cases where there is a difference of mineralogical composition between phenocrysts and ground-mass, or even where the latter consists of glass, no discontinuity of physical conditions is necessarily implied. It is supposed that the phenocrysts represent the excess of certain components over the eutectic ratio for the solution, while the ground-mass represents the eutectic itself. The phenomena of resorption are explained as due to supersaturation. This view is strongly supported by several facts, and especially by the occurrence within phenocrysts of inclusions of the ground-mass, commonly glass, which cannot have been formed under deep-seated conditions. This certainly appears to show that the solidification of phenocrysts and ground-mass was concurrent rather than successive.

[1] Crosby, 'Origin of Phenocrysts,' *American Geologist*, vol. xxv., 1900, p. 299.

Rock-forming Minerals.—The number of minerals which actually occur in the igneous rocks is very great, but many of these are rare and of little importance, either theoretical or practical. The important rock-forming minerals can, in practice, be referred to comparatively few groups, and if we disregard many of the names which systematic mineralogists and petrographers have needlessly conferred on slight variations, the number can be reduced to quite reasonable limits. Most of the minerals with which we have to deal are not pure compounds, having a fixed chemical composition, but are rather to be regarded as mixed crystals, composed of two or more isomorphous substances. When looked at in this way, the mineral groups can be, to a certain extent, correlated with the isomorphous groups of chemical constituents previously enumerated (see p. 230). The common rock-forming minerals may be classified on this basis as follows :—

I. Accessory minerals.
II. Ferromagnesian minerals.
III. Felspars and felspathoids.
IV. Quartz.

Group I. The Accessory Minerals.—This group includes a considerable number of minerals of very different composition and character, which occur widely distributed in small quantities. In certain exceptional cases, however, they may form an important part of the rock. Most of the rarer constituents of the magma are found to crystallise in the minerals of this group. It is impossible here to do more than mention a few of the more widely spread accessory minerals, such as apatite, sphene, zircon, ilmenite, and the various members of the spinel group, especially magnetite and chromite. For a full list reference must be made to the systematic works on petrology already cited.

Group II. The Ferromagnesian Minerals.—Under this heading are conveniently included a considerable number of silicates of various metals, especially magnesium, iron, and calcium ; in some of the subdivisions the alkali metals are important constituents, while other metals, such as chromium, manganese, barium, &c., frequently occur in small quantities. These minerals form the chief dark-coloured constituents of the rocks. The varieties recognised are rather numerous, but they may be subdivided and summarised as follows :—

(*a*) The micas.
(*b*) The amphiboles.
(*c*) The pyroxenes.
(*d*) The olivine group.

Besides these, tourmaline and garnet sometimes occur, but there is every reason to believe that the former at any rate is usually of secondary origin, and not an original product of magma consolidation.

All these minerals are silicates, and for the most part silicates of magnesium, iron, and calcium: in some cases, when derived from highly alkaline magmas, the alkali metals, especially soda, enter into their composition. Many of the mica group contain alkalies as normal constituents. The constitution of most of these minerals is fairly complex, but they can all be referred to one or other of the two chief acids of silica, orthosilicic and metasilicic acids. The micas, olivine and garnet are orthosilicates, while the amphiboles and pyroxenes are metasilicates.

Each of these groups contains numerous varieties, regarded by mineralogists as species, thus—

Micas—muscovite, biotite, phlogopite.
Pyroxenes—augite, enstatite, hypersthene, ægirine.
Amphiboles—tremolite, hornblende, arfvedsonite, riebeckite.

Group III. The Felspars and Felspathoids.—This group includes two natural subdivisions: (1) the true felspars and (2) the felspathoids, a number of minerals of varied and often peculiar composition, which occur only in rocks derived from the more alkaline magmas.

The felspars are essentially aluminosilicates of the alkali metals or lime, or mixtures of these. They divide themselves more or less naturally into two groups, the potash felspars, including orthoclase and microcline, both of which have the composition $KAlSi_3O_8$, and the plagioclase group, which are most conveniently regarded as isomorphous mixtures of the two end products $NaAlSi_3O_8$ (albite) and $CaAl_2Si_2O_8$ (anorthite). The members of this isomorphous group are conveniently designated *soda-lime* or *lime-soda* felspars, according to whether the soda or the lime molecule is dominant. There also occurs very commonly a minute intergrowth of orthoclase (or microcline) and albite, which is known as perthite. The discrimination of all these varieties depends on delicate optical tests, which are described in the special treatises before cited. The felspars are on the whole, perhaps, the most widely distributed and the most important of the minerals of the igneous rocks.

Group IV. Quartz.—In cases where the magma contains more silica than is required to combine with the basic oxides to form silicates, the excess of silica crystallises in the form of quartz.

Order of Crystallisation.—Although the order of crystallisation from the magma is by no means invariable, it has been established, as a result of observation and experiment, that the process is governed by certain general laws. Broadly speaking it may be said that the order is in the main one of increasing acidity, or as Rosenbusch prefers to state it, a *law of decreasing basicity*. In conformity with this we find that the accessory minerals crystallise first, then the ferromagnesian silicates, then the felspars and felspathoids, and finally quartz. There are, however, exceptions to this rule: thus, for example, microcline usually separates later than quartz, and in certain basic rocks it is common for the felspars to crystallise before the ferromagnesian minerals. The reason for these variable relations is not yet understood: it may depend upon different physical conditions, such as pressure, or more probably on the proportions in which the different constituents are present in the magma, since it is easy to prove on theoretical grounds that the order of crystallisation from a mixed solution is a function of the composition, and is independent of the absolute freezing-points of the components.[1] It must not be forgotten that most minerals are not pure, but are mixtures, and therefore their freezing points are not constant. The above considerations can of course only apply in full to the rocks which have consolidated in one stage. When consolidation has taken place in two stages, further complications are necessarily introduced.

The Classification of the Igneous Rocks.—The classification of the igneous rocks which is here adopted is a twofold one, based partly on physical characters and partly on chemical composition. The physical characters are controlled by the conditions under which the magma has cooled, and in particular by the rate of cooling; pressure may also have some influence here, but this is a somewhat obscure part of the subject. The most obvious division from this point of view is into *intrusive* and *extrusive* rocks. The intrusive rocks, however, show a very wide range of structure, so that it is found convenient to subdivide them again into two groups. The *plutonic* rocks are those large and deep-seated masses which have cooled slowly; they consist therefore entirely of crystals of various minerals (holocrystalline rocks). They are also usually coarse in texture, and typically non-porphyritic. In contradistinction to these are the *hypabyssal* rocks, the minor intrusions, which occur either as small independent masses, dykes or sills, or else as small offshoots or apophyses from plutonic intrusions. They have in consequence cooled somewhat quickly, since the loss of heat from small masses is rapid, owing to the large amount of surface in contact with cold rock in proportion to the total volume. These rocks commonly possess a character showing an approach to that of the extrusive rocks; they frequently contain more or less glass, and are often porphyritic. Frequently, however, they only differ from the plutonic rocks in their finer texture.

It must be remembered, however, that the distinction between plutonic and hypabyssal rocks is a purely arbitrary one, and among intrusions every gradation can be found from the coarsest granite, forming a mass many miles across, through all degrees of crystalline texture

[1] Harker, *Science Progress*, 1907, p. 239.

down to dykes and sills of pure glass, petrographically indistinguishable from the glassy lavas.

The extrusive or *volcanic* rocks, on the other hand are those which have been poured out on the surface as lava flows, and they possess the characters proper to their mode of origin. They generally contain more or less glass, and some are wholly glassy. The surfaces of lava-flows always show more or less of a slaggy or cindery appearance, and the lava itself is frequently spongy in texture from the occurrence of vast numbers of gas or steam bubbles. These criteria are usually sufficient to distinguish between an intrusive and an extrusive rock. Besides this, however, there is also the evidence provided by the alteration produced by the heated magma on its surroundings. A lava-flow can obviously alter only the underlying rock; and sediments subsequently laid down cannot be affected by it. An intrusive sheet injected along the bedding planes of an already existing rock must, however, alter the rock above as well as below, and this affords a certain test for discriminating the two classes.

For the reasons briefly sketched above it is found convenient to adopt a threefold classification of the igneous rocks, into the plutonic, hypabyssal and volcanic groups. Each of these groups may comprise rocks derived from magmas of any composition, so that under each heading a large number of rock-types is included. In fact, each group may and does comprise the whole range of variation of composition possible in an igneous rock. Hence it is necessary to adopt some other factor as a basis for the subdivision of these groups. The factor most usually adopted is chemical composition, which, as already explained, controls the minerals formed from the magma; hence in practice the basis of classification is a twofold one, partly chemical and partly mineralogical.

Since the most important constituent of igneous rocks is silica, its percentage naturally plays an important part in classification. According to the amount of silica present it has become customary to divide rocks into four groups, called *acid*, *intermediate*, *basic* and *ultrabasic* respectively. The acid group alone contains free quartz; the intermediate rocks are specially characterised by felspars with dominant alkalies; the basic group by felspars with lime dominating alkalies; while the ultra-basic group contains no felspar, or else a pure lime-felspar, without alkalies. However, if we attempt to classify by this means alone, we find that the intermediate and basic groups must contain rock types of very different character, which are clearly distinguishable into two sets characterised by special chemical and mineralogical peculiarities—the alkaline and subalkaline series before referred to (see p. 229). For this reason it becomes necessary to divide the intermediate and basic rocks into two groups, alkaline and subalkaline. The relations of the groups thus obtained may be shown diagrammatically, as follows :—

	Alkaline intermediate	—	Alkaline basic	
Acid				Ultrabasic
	Subalkaline intermediate	—	Subalkaline basic	

When this method of classification is applied to each of the physical groups, plutonic, hypabyssal and volcanic, we finally attain eighteen rock-types, as shown in Table I, p. 240. In this table the names given are those which are in common use ; they are for the most part quite arbitrary and possess no special meaning. In many cases, indeed, they are unsuitable, because they have been employed by different writers in varying senses. The nomenclature here adopted is in the main that given in Harker's 'Petrology for Students,' with slight modifications. No designation is as yet in general use to indicate the basic rocks of distinctly alkaline characters, since they have not yet been clearly separated from the subalkaline basic types. For want of a better name they are here called alkali-gabbro, alkali-basalt, &c.

In this table the first column includes the acid rocks, the second and third the intermediate, the fourth and fifth the basic, and the last column the ultrabasic types. This can, however, be stated in general terms only, and it is scarcely practicable to give any numerical values limiting the different families, because there exist, so far as we know, an infinite number of gradations between the types which have been chosen to characterise each of the groups. In fact, it may be said that there exists every transition both in the horizontal and in the vertical directions of this table. In this connexion it is important to notice that the vertical series represent similar magmas cooled under different conditions, while the horizontal series represent different magmas cooled under the same conditions.

This classification is an entirely arbitrary one, and is adopted solely as a matter of convenience. Names are applied to these families and also to minor variations occurring within their limits, but it must be understood that these names have not the precision of the nomenclature employed by biologists to designate genera and species. So far as we are aware, the composition of the igneous rocks is capable of indefinite variation, at any rate within certain limits. For this reason the classification of the igneous rocks is still in a very confused and unsatisfactory state.

Returning to the diagram given above, we may now substitute for the general designations there given the names of the rock-groups of Table I. Such a diagram can obviously be drawn up for each of the

TABLE I.

	Acid	Intermediate		Basic		Ultrabasic
Plutonic	Granite	Syenite	Diorite	Alkali-gabbro	Gabbro	Peridotite
Hypabyssal	Minor acid intrusions	Porphyry	Porphyrite	Teschenite	Dolerite	Peridotite-porphyrite
Volcanic	Rhyolite and Obsidian	Trachyte	Andesite	Alkali-basalt	Basalt	Ultrabasic Lavas

main divisions—plutonic, hypabyssal and volcanic. That for the plutonic group will be as follows :—

TABLE II.

Syenite—Alkali-gabbro
Granite < > Peridotite
Diorite— Gabbro

Mineralogical Composition of Plutonic Rocks.—We may now proceed to consider the mineralogical composition of a typical member of each family. For this purpose the plutonic rocks are again selected, since they are always holocrystalline, and there are no complications introduced by the presence of glass. The facts can be most easily set forth in a tabular form, as shown above in Table II, which is in reality only an expansion of the top line of Table I. Here transitional forms are ignored for the sake of clearness, but it must always be borne in mind that such exist. For example, two very common rock-types are quartz-syenite and quartz-diorite, which are intermediate between the granites and the syenites and diorites, respectively. Such instances might be multiplied indefinitely, but no useful purpose would be served by so doing.

The arrangement of the table on p. 242, perhaps requires some explanation. The minerals are divided into five groups : quartz, felspar, ferromagnesian minerals, felspathoids, and iron ores. In each group a number of names are given, but it is not meant to imply that all of these occur in any given rock. One, two or more of them may be present, or possibly all in exceptional cases. The ferromagnesian minerals present are largely used to characterise minor varieties of each group. Hence we arrive at such designations as muscovite-granite, hornblende-syenite, olivine-gabbro, &c. The felspathoids are not essential to the definition of the groups in which they occur, but they are characteristic of important subdivisions of these groups.

An examination of this table shows clearly that the distinction into alkaline and subalkaline series makes itself manifest in mineralogical as well as in chemical composition. This can be illustrated by tabulating some of the characteristics of each group in parallel columns, thus—

ALKALI GROUP.	SUBALKALI GROUP.
Quartz confined to acid members.	Quartz in intermediate members.
Alkali felspars occur in both acid and basic members.	Alkali felspars confined to acid members.
Felspathoids common.	Felspathoids absent.
Ferromagnesian minerals often soda-bearing.	Ferromagnesian minerals without alkalies.
Arfvedsonite, Riebeckite and Ægirine characteristic.	Rhombic pyroxenes characteristic.

Granite	Syenite	Diorite	Alkali-gabbro	Gabbro	Ultrabasic
Quartz					
Orthoclase Microcline Perthite Albite	Orthoclase Microcline Perthite Albite	Plagioclase (soda-lime)	Orthoclase	Plagioclase (lime-soda)	(Anorthite)
Muscovite Biotite Hornblende Augite Hypersthene Tourmaline	Biotite Hornblende Arfvedsonite Riebeckite Augite Ægirine	Biotite Hornblende Augite Hypersthene	Augite Ægirine Olivine	Augite Olivine Hypersthene	Olivine Augite Hypersthene Hornblende Biotite
	Nepheline Leucite Sodalite		Nepheline Leucite		
				Iron-ores	Iron-ores Spinels

I.—The Plutonic Rocks

The plutonic rocks are always wholly crystalline, and often very coarse in texture; they are usually not porphyritic, and the individual crystals do not generally show sharply defined outlines, owing to mutual interference during growth. The typical structure is that known as hypidiomorphic, i.e. the crystals are moulded on each other in more or less irregular forms. The earlier crystals naturally show the better outlines, and the relative order of crystallisation can usually be made out without much difficulty.

Granite.—The granites consist of quartz, alkali-felspars, with generally some plagioclase (oligoclase) and ferromagnesian minerals. They are classed according to the nature of the latter. The following types are common: muscovite-granite, muscovite-biotite granite, biotite-granite, biotite-hornblende granite, hornblende-granite. Hornblende-granites are usually less acid than the granites with mica, and often contain a good deal of accessory plagioclase, thus showing an approach to the quartz-diorites. Augite-granites are uncommon, while hypersthene-granites are very rare indeed. Many granites contain tourmaline, but it is doubtful how far this is an original constituent: in many cases it is certainly due to alteration of other minerals by pneumatolysis.

Large granite masses are rarely of the same texture throughout. They are often traversed by veins or dykes of coarser or finer character. The coarse veins are called pegmatite, and their origin is discussed elsewhere (p. 254). The fine-textured acid veins (aplite) appear to be of a similar character so far as regards their manner of formation. Granites frequently show abundant xenoliths.

Syenite.—The magma of this group differs chiefly from that of the granites by containing less silica, while the alumina and alkalies are correspondingly higher. Consequently the dominant mineral is an alkali-felspar, and in more basic varieties felspathoids occur. Hence the syenites are typically alkaline rocks. In many cases soda is dominant over potash, and perthite is characteristic. The ferromagnesian minerals also are often soda-bearing, including such varieties as arfvedsonite, riebeckite and ægirine. Many varieties contain quartz, and show a transition to the alkaline granites. The true syenites, with little or no quartz, can be divided into two groups, characterised by presence and absence of felspathoids, as follows:—

Without felspathoids: hornblende-syenite, augite-syenite, mica-syenite.
With felspathoids: nepheline-syenite, leucite-syenite, sodalite-syenite.

Syenites are a very abundant rock-type in alkaline petrographical provinces, and occur in large masses quite comparable to the great granite intrusions. Their structure also is very similar to that of the granites, and they show pegmatites, aplites and pneumatolytic phenomena on a large scale, often resulting in the formation of rare minerals.

Diorite.—Under this heading are included a considerable number of rock-types with a fairly wide range in chemical composition. The dominant felspar is a plagioclase with soda in excess of lime ; the magma is distinctly subalkaline, so that felspathoids never occur and the ferromagnesian minerals are not soda-bearing. In some varieties a good deal of quartz occurs ; these are separated as *tonalites*, and they show an approach to the hornblende-granites. On the other hand, some unusually basic varieties contain olivine in small quantity. Tonalites are very common as large intrusions in subalkaline provinces, but true diorites are rather rare.

Monzonite.—This name is applied to a group of rocks which are in some respects intermediate between the syenites and diorites. Their relationship to the former group is shown by the occurrence of an alkali-felspar, usually orthoclase, while the presence of a rather basic plagioclase, andesine or labradorite, connects them with the diorites and gabbros. They are thus intermediate in character between the alkaline and subalkaline groups. They show a fairly wide range of composition, comprising acid varieties with quartz and basic ones with olivine (e.g. Kentallenite).

Gabbro.—This group, in the narrower sense here employed, includes the basic subalkaline rocks, characterised by the presence of abundant basic lime-soda felspar, and augite, with or without olivine. Minor varieties contain hypersthene and hornblende. Iron-ores are generally abundant, and are frequently titaniferous. Consequently the rocks are generally dark in colour and heavy. Gabbros occur in bosses and laccoliths of considerable size, though not so large as in the case of the acid rocks.

Alkali-gabbro.—In accordance with the scheme of classification previously given, we must place in a separate class the alkaline basic rocks, characterised by the presence of orthoclase and felspathoids : such are theralite or nepheline-gabbro, and missourite or leucite-gabbro. Borolanite, which is usually described as a leucite-syenite, also belongs here, since it contains only 48 per cent. of silica. These rocks are not common, and are best developed in America.

Ultrabasic Plutonic Rocks.—This group includes a large number of rock-types of variable mineralogical composition to which a variety of unnecessary names have been applied. Broadly speaking, they may be divided into two groups—the *peridotites*, characterised by the presence of much olivine and absence of felspar ; and the *anorthosites*, which consist chiefly of lime-felspar (anorthite). When olivine rocks contain a little felspar they are called *picrites*, and these form a transition to the gabbro group.

Serpentine Rocks.—The minerals of the ultrabasic rocks are specially liable to decomposition, giving rise to hydrated silicates of magnesia (serpentine) and iron-ores. They are dark-green, red or black in colour, with a peculiar mottled appearance and greasy lustre.

II.—The Hypabyssal Rocks

This group is rather an artificial one, and no well-defined characters can be given for it. It includes types varying in structure from holocrystalline to wholly glassy, and from a fairly coarse texture to cryptocrystalline structure or unindividualised glass. The range of variation in chemical composition is parallel to that of the other classes, but owing to the fact that many hypabyssal rocks are differentiated offshoots of large plutonic masses, it is difficult or impossible to draw up a satisfactory scheme of classification for them. The intermediate and acid types are often markedly porphyritic, while many of the acid ones also show a peculiar intergrowth of two minerals, usually quartz and felspar, which is known as granophyric or micrographic structure.

The Acid Intrusives.—This group includes the hypabyssal representatives of the granite magma, and comprises rocks showing wide variations in structure. In fact, a complete transition can be traced from the plutonic to the volcanic group, i.e. from holocrystalline to vitreous. We may, however, recognise three main groups. (1) *Micro-granite* and *granophyre:* these show either the granitic structure on a small scale, or else the micrographic intergrowth as before defined. (2) *Granite-porphyry* and *quartz-porphyry* : these are markedly porphyritic rocks with a crystalline ground-mass. (3) *Pitchstone*, a glassy rock either with or without porphyritic crystals. These latter are identical, except in their intrusive character, with the volcanic obsidians.

Syenite-porphyry Group.—Here are comprised the smaller intrusions of the alkaline intermediate magma, which include a variety of rock-types of very varying structure. Many of them are markedly porphyritic, resembling the granite-porphyries except in the absence of quartz-phenocrysts. Others, such as the *orthophyres* and *bostonites*, show more affinity to the trachytes of the volcanic group, often exhibiting distinct flow-structures. The characteristic and most abundant mineral is an alkali-felspar, and the ferromagnesian minerals also are often soda-bearing, as in the syenites. *Tinguáite*, a variety with nepheline, corresponds to nepheline-syenite.

Porphyrite Group.—These rocks are distinguished from the preceding by the fact that the dominant felspar is a plagioclase with soda in excess of lime. They correspond, therefore, to the diorites. Most of them are distinctly porphyritic with a microcrystalline ground-mass. Some of the non-porphyritic rocks usually described as quartz-dolerites undoubtedly belong here, forming the hypabyssal representatives of the tonalite group.

Dolerite Group.—The term dolerite has now superseded diabase for the hypabyssal forms of the gabbro magma, which form a very widely-spread rock-type in the form of dykes and sills. The principal varieties recognised are *quartz-dolerites* (see preceding paragraph), *dolerite proper* and *olivine-dolerite.* Non-porphyritic forms are perhaps the more common. The texture is usually fine, but sometimes the central parts of large sills approach the gabbros in structure.

Teschenite Group.—This name may be applied to certain basic intrusions of doleritic habit and alkaline chemical composition, often containing felspathoids, such as nepheline, leucite and analcime, with or without orthoclase; they correspond to the alkaline-gabbros.

Ultrabasic Small Intrusions.—Owing to the fact that the ultrabasic magmas do not visibly occur in large masses, it has not in most cases been found possible to discriminate between those of plutonic and those of hypabyssal character. In a few localities, however, such types as *picrite-porphyrite* have been described. They differ chiefly from the plutonic rocks before described in that they are more or less clearly porphyritic, the minerals being essentially the same.

Lamprophyre Group.—These form a peculiar and rather aberrant family of dyke-rocks, with a wide range of chemical composition. They are difficult to reconcile with any formal scheme of classification, probably because they are largely differentiation products of plutonic magmas. They are composed chiefly of ferromagnesian minerals, with only subordinate felspar; if the rock is porphyritic, it is only the ferromagnesian constituents that occur in the first generation. The group, as at present defined, seems to include both alkaline and subalkaline types, and some are almost ultrabasic in composition. They occur for the most part as apophyses of large plutonic masses, as small sills or dykes. Many different names are applied to sub-varieties, and the whole group is often spoken of collectively as the *mica-traps.*

III.—The Volcanic Rocks

This group is here taken to include all the true lavas, the extrusive products of vulcanicity. Volcanic rocks have cooled quickly at atmospheric pressure, and their structure is a direct consequence of the physical conditions under which the cooling took place. They are usually porphyritic, and the ground-mass commonly includes some glassy or devitrified residue, while some, especially the more acid varieties, may be chiefly or wholly glassy. Vesicular and amygdaloidal structures are common, and fluxion-phenomena, such as flow-lines, banding and drawing-out of vesicles, also prevail.

Rhyolite.—This group includes all the truly acid lavas, and may be conveniently divided into two groups: *Obsidian*, which includes varieties consisting wholly or chiefly of glass, and *Rhyolite* proper, comprising the crystalline varieties. The structures of the Obsidian group are characteristic and peculiar, but cannot be described here. They often undergo devitrification, giving rise to a group of fine-textured rocks conveniently known by the old field-term *felsite*. The Rhyolites proper consist of alkali-felspars and quartz, with commonly some ferromagnesian mineral; the ground-mass is also crystalline, of varying texture. Spherulitic and nodular structures are common.

Trachyte.—This group as here defined comprises the alkaline intermediate lavas, corresponding to the syenite group. It can be subdivided into *trachyte* proper, without felspathoids; *phonolites*, with nepheline; and *leucitophyres*, with leucite. The rocks are commonly holocrystalline, and show a distinct parallel arrangement of felspar prisms, due to flow. This is the typical trachytic structure. The dominant minerals are the alkali-felspars, orthoclase, sanidine, perthite or anorthoclase, together with mica, hornblende, augite, ægirine, riebeckite, &c. Coloured minerals are not commonly abundant.

Andesite.—The Andesites are intermediate lavas, consisting chiefly of soda-lime felspar and ferromagnesian minerals; they correspond in composition to the diorites; varieties with quartz, corresponding to the tonalites, are called *dacites*. The commonest ferromagnesian minerals are hornblende, augite, hypersthene and biotite. They are usually porphyritic, and the ground-mass consists of lath-shaped felspars and grains of ferromagnesian minerals, with in general a fair amount of glass. In some varieties they are almost wholly glassy, while others show the intersertal structure which is so characteristic of the basalts.

Alkali-Basalt.—In certain parts of the world, and especially in Italy and Western America, there are to be found peculiar rock-types which, although distinctly basic, yet contain a considerable amount of alkali-felspar, usually orthoclase. Some of these doubtless represent the alkali-gabbro group, while others, which contain lime-felspar also, should probably be referred to the monzonite magma. Here also must be included certain highly alkaline types, which are characterised by the presence of nepheline or leucite in addition to felspar and ferromagnesian minerals. Those without olivine are the tephrites, and those with olivine the basanites.

Basalt.—This term is here used to describe the basic lavas of subalkaline composition, which consist essentially of lime-soda felspar and augite, with or without olivine. Hornblende-basalts and hypersthene-basalts are also known. Some varieties are porphyritic, with a ground-mass resembling that of the andesites; whereas others possess the intersertal structure: that is to say, they consist of lath-shaped felspars, with more or less shapeless grains of augite, olivine, &c., between them and a certain amount of interstitial glass. Glassy varieties are rare, and are almost confined to thin selvages on the margins and surfaces of flows and dykes. Basalts occur in enormous masses, both as the products of ordinary volcanoes and as the result of fissure-eruptions.

Ultrabasic Lavas.—Here are included a large number of rock-types of variable composition, which may be conveniently summarised under two heads: the *Limburgite* group, consisting chiefly of olivine, augite and glass, without any felspar or felspathoids; and the *leucite* and *nepheline lavas*, in which felspathoids are abundant and characteristic, while felspar is absent. Numerous names are applied to the variations possible in this group, such as *leucitite*, *nephelinite*, *nepheline-basalt*, &c. Another peculiar type is *melilite-basalt*.

Differentiation of Igneous Magmas.—Reference has already been made in this chapter to the fact that large masses of igneous rocks frequently show variations of chemical and mineralogical composition in different parts, although there is sufficient similarity in the general character of all the varieties to suggest a genetic relationship. This applies to igneous complexes on a comparatively small scale, and the same idea may be extended to petrographical provinces. Of late years much attention has been devoted to this branch of theoretical petrology, and it has come to be generally believed that such similarities really do indicate a common origin for the rocks in which they occur. It is supposed that the successive intrusions of an igneous complex have been derived by some chemical or physical process from one original magma, and this hypothetical production of different rock-types from one originally homogeneous magma has come to be known as *differentiation*. Consideration of the physical or chemical causes of this separation may be deferred until we have examined the evidence of its occurrence as seen in the field.

Sequence of Rock-types.—Many attempts have been made to establish a definite order of succession of the different rock-types, from acid to basic or the reverse. Different authorities have arrived at very diverse conclusions, but this may perhaps be explained by the fact that some studied extrusive rocks and others intrusive. It appears probable that the sequence is different in these cases, and that even in the larger and smaller intrusive series it is not the same. It must be confessed that the evidence is very conflicting and far from conclusive, but the general conclusions now arrived at may be summarised somewhat as follows. In the volcanic rocks an eruptive series usually seems to begin with an intermediate type, trachyte or andesite, and at later stages the lavas may vary either towards the acid or the basic end of the series, with frequently a relapse to the other extreme as a final stage. A common succession is andesite, rhyolite, basalt; this sequence seems to be of common occurrence in America and elsewhere. In other localities the acid phase comes last, and the only general conclusion which we are at present able to draw is that frequently the succession seems to be one of increasing divergence from a mean type. In the case of the plutonic rocks, however, rather more definite results have been obtained. In the most satisfactory cases the succession seems to be almost invariably from basic to acid, whereas in the hypabyssal rocks an inverse succession has in some cases been established. This double sequence is very clearly seen in the case of the Tertiary igneous rocks of Skye, as described by Mr. Harker. Here the full succession in the three phases is as follows:—

Volcanic phase.	1. Small intermediate eruptions of trachyte and agglomerate. 2. Plateau basalts (fissure-eruptions).
Plutonic phase.	3. Ultrabasic laccoliths (picrites, peridotites, &c.). 4. Gabbro laccoliths of the Cuillin Hills. 5. Granite and granophyre laccoliths of the Red Hills.
Phase of small intrusions.	6. Acid dykes and sills, quartz-porphyries and pitchstones. 7. Great group of dolerite sills. 8. Ultrabasic sills and dykes.

So far as the plutonic rocks are concerned, the Devonian intrusions of the Christiania district obey the same general law, each successive laccolith being more acid than the preceding one, so that there is a series from olivine-gabbro, through nepheline-syenite and syenites of increasing quartz-content, to granite. In these cases it is supposed that the different partial magmas have split off under deep-seated conditions from a primitive magma having special characteristics, which therefore are found in the whole of the rocks of that series and district. This gives rise to igneous complexes when on a small scale, and to petrographical provinces when on a large scale, and is called by Brögger *deep-magmatic differentiation.*

Laccolithic Differentiation.—When a single intrusion is examined in detail it is frequently found not to be uniform in composition, but to show variations which may possess a certain regularity of arrangement. Most commonly the marginal parts are more basic than the interior, and show a higher proportion of iron-ores and ferromagnesian minerals. A very well known example in this country is the gabbro of Carrock Fell, investigated by Mr. Harker. Here the silica percentage ranges from 59 at the centre to 33 at the margin, and the percentage of ilmenite rises in the same direction from 1 to 25. Similar relations are seen in a less marked degree round most intrusions, and the phenomenon seems to be a general one. Several explanations have been put forward to account for it, but the most probable is Mr. Harker's theory: successive supersaturation for constituents of highest freezing-point in a cooling magma, with consequent molecular flow of material towards the peripheral region, in an attempt, as it were, to restore the equilibrium destroyed by separation of minerals in the solid state. Each constituent is thus concentrated at the margin in the order of its freezing-point, and when the magma becomes too viscous to allow of further molecular movement, the process stops. By this means basic material is drained off from the centre, which is ultimately left more acid than the mean type. This accounts, for example, for the presence of quartz in the central parts of the Carrock Fell gabbro. Very similar phenomena are seen at the margins of the Christiania laccoliths, and the whole process is called by Brögger *laccolithic differentiation.* It is noteworthy that the Carrock Fell intrusion comprises also an acid member having the composition of a granophyre, but still showing affinities to the gabbro. The acid intrusion is later than the basic one, and it is probable that the two have been derived by magmatic differentiation from one original magma, so that this intrusive complex shows examples of both phases of differentiation.

Complementary Series.—The minor intrusions round a large rock-mass, which may be regarded as apophyses, frequently show a clear separation into two types, an acid and a basic. For example, the dykes around the Shap granite include quartz-porphyries and lamprophyres, while around the Cheviot granite we find quartz-porphyries and mica-porphyrites. Again, in the Christiania district the dykes belonging to the most basic intrusions (essexite, or olivine-gabbro) include bostonites, which are almost pure alkali-felspar rocks, and therefore acid, and camptonites, a distinctly basic hornblende-lamprophyre. According to Brögger, these are to be regarded as differentiation products of the essexite magma.

Causes of Differentiation.—From the foregoing examples it may be regarded as established that some kind of separation into portions of varying composition takes place in igneous magmas, both before and after intrusion. The origin of magmatic differentiation is obscure, but may be explicable on the same lines as sketched out for the Carrock Fell gabbro. The action of gravity has also been invoked as an explanation, as well as various physical laws such as Soret's principle, and the law of Gouy and Chaperon. The question must be regarded as still *sub judice.* In the case of the marginal modifications of laccoliths, some cases may be due to absorption and fusion of basic material from the surrounding rocks by the heated magma, but until lately not much importance has been attached to assimilation of material: at the present time the idea is again beginning to attract attention, in connexion with certain deep-seated intrusions (batholiths, &c.), and some American petrologists are inclined to attach much importance to it.

Pneumatolysis.—Among the processes of alteration in rocks which involve a change in the total bulk composition of the mass, perhaps the most important is that class of phenomena to which the general name of pneumatolysis has been given. In the conception of pneumatolysis, as at present understood, two distinct ideas are involved: in the first place it includes a series of processes which are believed to take place in the igneous magma itself during the final phases of its consolidation, and in the second place changes brought about in the surrounding rocks by actual addition of material from the intrusive magma.

As the name implies, pneumatolysis may be defined as the changes produced by the action of heated gases and vapours of high chemical activity. The processes have been most completely studied in the case of granite magmas, and our own country supplies some very typical examples in the granites of Devon and Cornwall. The effects of pneumatolysis due to syenite and gabbro magmas have also been very thoroughly investigated in Scandinavia, and the general character of the phenomena is found to be very similar in all cases, though differing a good deal in detail. It will be most convenient to deal first with pneumatolytic processes as affecting the final constitution of igneous rocks, leaving the external effects for separate consideration, since they really appertain to the domain of metamorphism in the wide sense of the term.

Pneumatolysis in Igneous Magmas.—Besides the constituents which go to form the ordinary minerals of the igneous rocks, the magma appears to contain in comparatively small amount a large number of other elements, both metallic and non-metallic, which form compounds of a special character: some of the most important of this latter class are the metallic ores, and certain minerals containing fluorine, boron, and other elements of low atomic weight. In all probability the metallic and other elements of this class were diffused uniformly through the magma when in a state of complete fusion, but as the mass cooled the basic materials crystallised first, while the more siliceous material drove out the active elements, especially the gases, and concentrated them in an acid residual magma. The gases carried along with them the elements with which they were able to form volatile compounds, and concentrated them in the residual magma. These volatile compounds probably to a certain extent decomposed minerals already formed and gave rise to new minerals; e.g. formation of tourmaline from ferromagnesian minerals and from felspar. In some cases also these volatile compounds seem to have escaped through fissures from the cooling magma, and gave rise to metasomatic changes in the surrounding rocks.[1]

The Land's End District.—The pneumatolytic modifications of the granite of the Land's End have been investigated by Messrs. Reid and Flett, and their conclusions seem to apply to other cases of the same general type. They may be summarised as follows. The agents which caused the changes were vapours emanating from the granite magma at a late stage of cooling. These vapours consisted chiefly of water at a very high temperature, together with compounds of boron, fluorine, lithium, and phosphorus. Most of the metalliferous ores came from the same source, certainly tin, and probably uranium, tungsten, copper and iron. For the present the metalliferous ores may be disregarded, and attention confined to the changes produced in the granite itself by the action of the more volatile residual constituents of the magma. For this purpose the more important of these are water, fluorine, boron, and lithium compounds, together with tin and beryllium.

In accordance with the presence or absence of one or other of these constituents various minerals are produced. It may be safely assumed that in all cases water in the form of vapour or superheated liquid is present: when the dominant constituents are fluorine and boron together, tourmaline is formed; fluorine alone gives topaz and fluorspar; lithium gives lithia mica; superheated water gives muscovite when acting on felspar; and beryllium compounds form beryl. Tin, probably in the form of volatile tin fluoride, accompanies the other minerals.

In accordance with these facts three chief types of pneumatolysis may be recognised.

(1) Tourmalinisation.—Vapours containing fluorine and boron act on the ferromagnesian minerals and the felspars of the granite, and form new compounds with their original constituents. In the first place, they attack the biotite, forming brown tourmaline. The result is tourmaline granite. If the action is more intense the felspar is also attacked, and converted into an aggregate of tourmaline and quartz. A good example of this is the well-known rock Luxullianite, in which the change is only partially complete, so that a considerable amount of pink felspar still remains. When the whole of the felspar is

[1] Hill and Macalister, 'Geology of Falmouth and Truro,' *Mem. Geol. Survey*, 1906, p. 167 *et seq.*

destroyed, so that the only minerals present are quartz and tourmaline, it is called *Schorl-rock*. The margin of the granite is usually converted into this modification. Subordinate white mica, apatite, topaz, and tinstone may also be present.

(2) Greisening.—The margin of the granite mass, and especially the walls of vertical fissures, often show layers a few inches thick of the modification known as *Greisen*, which consists chiefly of quartz and white mica, usually lithia-bearing, with sometimes a little topaz, tourmaline and apatite. The formation of greisen seems to be due chiefly to superheated steam and fluorine, with little or no boron. It is clear that the vapours ascended from below through fissures, and the alteration took place after solidification of the granite, since greisen is only found lining the walls of open fissures.

(3) Kaolinisation.—The third kind of pneumatolysis is most common near the centres of granite masses, and occurs chiefly in vertical columns or pipes with a more or less circular section. The granite is here converted into an aggregate of kaolin, muscovite and quartz, which often becomes friable. The quartz and mica are unaltered, but the felspar is represented by soft white aggregates of kaolin with a little quartz.

Many of the elvan dykes have also undergone pneumatolysis, and all stages in the formation of schorl-rock and greisen may be seen in them. Tinstone has often been introduced. Kaolinisation is unknown in elvans.[1]

Pneumatolysis in Basic Magmas.—The type of pneumatolysis which occurs in basic magmas, and especially in gabbros, has been studied in Scandinavia by Brögger and by Vogt. The general character of the phenomena is found to be much the same as in acid magmas, but the elements chiefly concerned are different. Here the process of extraction is largely due to chlorine and phosphoric acid; and in gabbros we find veins of rutile and apatite, which have been formed in a manner analogous to the veins of tinstone, &c., in the granites. It is worthy of note that the apatite of basic rocks is chlor-apatite, whereas in the acid rocks the fluorine-bearing variety occurs. Another interesting change which sometimes takes place in gabbros and other basic rocks is *scapolitisation*, and this is also believed to be of pneumatolytic origin. The original felspar of the gabbro is decomposed and converted into scapolite, while the pyroxene recrystallises as amphibole. Scapolite rocks of this kind are known in Norway, Canada, and elsewhere. Other rock-types containing the same mineral appear to be due to the contact metamorphism of impure limestone. (See p. 263.)

[1] Reid and Flett, 'The Geology of the Land's End District,' *Mem. Geol. Survey*, 1907, p. 67 *et seq.*

Pegmatites.—Closely allied to pneumatolysis, certainly in many cases, is the origin of the coarse-textured veins and masses of crystalline minerals which are collectively known as pegmatites. These are dykes, veins or irregular masses, usually either traversing igneous rocks of more normal texture, or occurring as offshoots or fringes of such masses. They are often of very coarse texture, so that individual crystals may be measured by inches or even by feet. They also show very frequently a strong tendency to a *graphic* intergrowth of two minerals, usually quartz and felspar. They possess as a rule the same general mineralogical composition as the normal igneous rock with which they are associated, but there is usually a somewhat higher proportion of acid minerals, and they are frequently characterised by the occurrence of special minerals, often including compounds of the rarer elements.

There has been a good deal of difference of opinion as to the actual manner of origin of pegmatites. For example, Sterry Hunt[1] maintained that they were exclusively of aqueous origin, having been formed entirely by deposition from solution in water. Of late years, however, it has been agreed that the majority of pegmatites are closely connected with intrusions of large bodies of igneous rock, usually at a considerable depth, and that their formation represents a late phase of consolidation, which is in close connexion with the processes of pneumatolysis above described. All that has been said in the last section as to concentration in the residue of the magma applies here also, and it is clear that particular importance must be attached to the presence in this residue of large quantities of heated water. The frequency of graphic structure is easily explicable on the assumption, now generally accepted, that it is characteristic of the crystallisation of mixtures in eutectic proportions, or nearly so. When pegmatitic offshoots of igneous intrusions are traced outwards into the surrounding rocks, it is often found that a gradual change of character occurs. Near the intrusion they are merely dykes of igneous rock, often containing rare minerals: further away they become less and less like the intrusion; and owing to the progressive failure of certain minerals they pass gradually into veins, which can often be traced into masses of pure quartz, quartz-veins of the ordinary type, which are so common in most of the older disturbed areas of sedimentary and igneous rocks.

The extremely coarse texture of pegmatites is due to the presence of considerable quantities of water and other fluxing agents, which keep the solution in a very mobile state, and thus favour the formation of large crystals by free diffusion of molecules. When such fluxing materials are absent, the solution is more viscous, there is less diffusion and more centres of crystallisation, and a fine-grained rock called aplite is formed.

[1] *Chemical and Geological Essays*, 1875, p. 191.

Minerals of Pneumatolysis.—The minerals formed in the ordinary pneumatolysis of igneous rocks and in pegmatites naturally vary according to the chemical composition of the residual concentrated magma. As before stated, the characteristic elements of the acid type are fluorine, boron, lithium and beryllium, all elements of low atomic weight, together with certain of the heavy metals, tin, tungsten, copper and iron. The mode of occurrence of the latter group will be dealt with later on, under the heading of mineral veins (see p. 275). The characteristic minerals of the granitic type of pneumatolysis, therefore, are tourmaline, topaz, fluor-spar, beryl, lithia-mica, &c., in the igneous rocks, and in altered argillaceous and arenaceous sediments, together with axinite, datolite, &c., in altered calcareous rocks. A good deal of quartz is formed in most cases by the setting free of silica on decomposition. In basic magmas, on the other hand, the characteristic elements are titanium, phosphorus and chlorine, and these give rise to rutile, ilmenite, and other minerals rich in titanium, apatite, and various members of the scapolite group. Besides these, an immense variety of minerals, often containing rare elements, have been described by Brögger from the pegmatite dykes of South-west Norway. Some of these are associated with syenites and nepheline-syenites, and some with gabbros. They include many compounds of zirconium, thorium, and other metals which are now of much commercial importance for the manufacture of incandescent gas and electric lamps.

CHAPTER XIV

METAMORPHISM

Definition of Metamorphism.—The rocks comprising the lithosphere do not commonly remain precisely in the condition in which they were formed, but undergo alterations of various kinds, by which they assume characters different from what they originally possessed. By some writers the term *metamorphism* is used to express all changes, of whatever kind or origin, occurring in rocks subsequent to their formation, whereas by others its use is restricted to cases where the changes can be traced to the effects of increase of temperature or pressure, or both combined. It is in this sense that the term will be used here; the effects of natural processes, chemical or physical, acting at normal temperatures and pressures, are considered separately, under the headings of *weathering* and *metasomatism* (see Chapter II and p. 271). The processes which are comprised under the general heading of weathering are mostly of a *destructive* nature, resulting in the formation of simpler compounds from more complex ones; metasomatic processes are those which involve addition of material from extraneous sources, leading to a change in the total chemical composition of the rock; whereas metamorphism proper consists in a rearrangement of the molecules, and generally results in the formation of more complex compounds from simpler ones.

Stable and Unstable Compounds.—The whole question of alterations in rocks, however brought about, depends on the stability or otherwise of their components under the physical conditions in which they find themselves. Every mineral is stable only within certain limits of temperature and pressure, and if these limits are passed the molecules tend to rearrange themselves in other forms proper to the new conditions. Again, most rocks are heterogeneous, and their constituents may react with each other to form new chemical compounds; these changes are controlled by well-known physical and chemical laws. The chief agents which bring about changes in rocks are heat and pressure, aided to a great extent by water, and substances dissolved in water, and gases. In ordinary weathering the action of water and solutions are of the greatest importance, while metasomatic processes may be due to solutions, or gases, or both. Metamorphism in the strict sense here employed is mostly due to heat and pressure acting alone, or in conjunction with the other agents mentioned.

Zones of Alteration.—According to Van Hise,[1] the accessible part of the lithosphere can be divided into three zones or belts, which, however, are not sharply limited. The outermost, or *belt of weathering*, includes the region of low temperature and low pressure, where the processes are mostly destructive, involving disintegration of the rocks with much solution of material by ground water. Below this comes the *belt of cementation*, where the material carried in solution by the ground water is to a large extent deposited, solidifying the rocks and originating certain metasomatic processes by addition of new material to existing compounds: here the temperature and pressure are still moderately low, and the rocks are well below their melting point. This graduates downwards into the region of *constructive metamorphism* (anamorphism), where the temperature and pressure are high. This is the region in which rearrangement of molecules takes place, so that new minerals are formed and far-reaching changes in the physical state of matter are brought about. Frequently, however, conditions similar to those of this deep-seated region are brought about in the upper layers of the lithosphere by special processes, of which the chief are intrusion and extrusion of igneous rocks, and earth-movements on a large scale.

Classification of Metamorphism.—Metamorphism may be defined as the production of new minerals or new structures, or both, in pre-existing rock masses, under the influence of heat or pressure. As a general rule the formation of new minerals is due to heat, whereas pressure sets up new structures: however, intense pressure is always accompanied by evolution of heat, owing to friction, and this often leads to chemical reactions between the constituents of a rock and consequent production of new minerals. In accordance with this rule metamorphism may be most conveniently divided into *thermal* and *dynamic*. Thermal metamorphism may be brought about in various ways: for example, the accumulation of thick masses of sediment may raise the temperature of part of the crust, by preventing escape of heat from the earth's interior: this is known as a rise of the geo-isotherms. This process may take place on a very large scale. However, the more commonly occurring and best known examples of thermal metamorphism are due to the intrusion or extrusion of masses of igneous rock. Since these are usually of comparatively limited extent they are sometimes spoken of as local metamorphism, but a more satisfactory term is *contact metamorphism*. Dynamic metamorphism is due to stresses set

[1] Van Hise, *Journ. of Geol.*, vol. iv., 1896, p. 195 *et seq.*

up by earth-movements, and since these are often very widespread in their distribution, the attendant phenomena are frequently known as regional metamorphism. The classification here adopted is the simple division into thermal and dynamic.

Thermal Metamorphism

Rise of the Geo-isotherms.—There is evidence to show that at certain periods in some regions the temperature of the rocks now exposed at the surface has been so much increased as to set up far-reaching changes in their constitution, both physical and mineralogical. This is supposed to be due to deposition of great thicknesses of sediment in a sinking area, by which the lower layers were brought into a zone of very high temperature. A case of this kind has been described in the Rainy Lake region of Canada.[1] The lowest rocks here exposed are coarsely crystalline gneisses, the Laurentian series, and these are now overlain by two thick sedimentary series, also of pre-Cambrian age, the Coutchiching and Keewatin series. It is clear, however, that the Laurentians in their present condition are newer than the rocks above them, since they contain fragments of the latter, more or less altered by heat, and dykes and veins can be traced from the Laurentian into the Coutchiching and Keewatin series. Where the Laurentians are overlaid by the Coutchiching series they are for the most part highly acid biotite-granite-gneisses, with abundant quartz, but where they are overlain by the Keewatin series, the upper part of the Laurentian consists of hornblende-syenite-gneiss, without quartz, whereas the lower part is quartzose. It is concluded, therefore, that the Laurentian series, as at present existing, has been formed by fusion and recrystallisation of sedimentary rocks belonging to the Coutchiching, Keewatin and perhaps older series. This fusion has gone on up to a certain irregular surface, which now forms the floor on which the sedimentary series rest.

Contact Metamorphism.—The best-known cases of thermal metamorphism are those which have been brought about by masses of igneous rock. Whenever a lava stream flows over a surface of rock it induces a certain amount of alteration, but this is usually of trifling importance, owing to the rapid cooling which the lava undergoes. With intrusive masses, however, the case is very different. The cooling of a large intrusion is necessarily a slow process, so that the surrounding rocks are maintained for a long period at a high temperature, and great effects are frequently produced in this manner. The intensity of

[1] Lawson, 'Rainy Lake Region of Canada,' *Rep. Geol. Surv. Canada*, 1887–88, New Series, vol. iii. part i. Report F.

the alteration is dependent upon several factors, of which the chief are the size and the temperature of the intrusion, the rate of cooling, and the character of the rocks acted on. It is found as a result of observation that acid intrusions produce a much higher degree of alteration than basic ones. This may depend upon the initial temperature of the intrusive magma, or upon the chemical character of the gases and vapours which accompany it. In all probability both these considerations are of importance, and it must also be borne in mind that the largest intrusive masses with which we are acquainted are of an acid character. The most important factor, however, in determining the petrographical character of the rock-types which result from metamorphism is the original constitution of the rocks themselves. Some rocks appear to be inherently much more susceptible to alteration than others, and this depends chiefly upon the range of stability under different conditions of the minerals of which they are composed.

Thermal Metamorphism of Sedimentary Rocks

The most important groups of sedimentary rocks are conveniently classed as arenaceous, argillaceous and calcareous, and each of these groups when metamorphosed gives rise to a characteristic type of alteration-product.

Arenaceous Rocks.—These comprise the coarser-grained sediments, of which quartz is the most important constituent, although many other minerals are often present. If the rock consists entirely of quartz no chemical reactions can occur, and the only possible change is recrystallisation. The sand grains lose their outline, and the distinction between grains and cement is obliterated, the whole forming a mosaic of quartz crystals usually of very irregular form. Such a rock is known as a quartzite. Cases are also known in which pure sandstones or grit have been partially or wholly fused, and have solidified in the form of glassy silica. Such vitrified rocks are, however, rare.

When an arenaceous rock consists of an aggregate of particles of different composition, chemical actions can occur between the constituents under the influence of heat, and new minerals are formed. The general composition of the impure arenaceous rocks is much the same as that of the argillaceous group, although the proportions in which the constituents occur may be very different; hence to study each group separately in detail would involve a good deal of repetition, and the general principles underlying the formation of new minerals in such rocks may be conveniently treated of here.

Formation of New Minerals in Siliceous and Argillaceous Rocks.—The chemical constituents, qualitatively considered, of the sandy and muddy sediments are the same as those of the igneous rocks, although quantitatively there may be much variation. Many of these constituents exist in the form of decomposition products of unstable minerals, and others as particles of minerals which are of greater stability. On the whole, the minerals which exist in the sediments are of simple composition, and some of the material may be in the amorphous form. Under the influence of heat the constituent molecules of these particles undergo rearrangement and form minerals, some of which are identical with those of the igneous rocks, while others are unknown in that class.

The most important chemical constituents of this class of rocks are silica, alumina, magnesia, and oxides of iron, with subordinate lime and alkalies. According to the proportions in which these are present, and the temperature to which the whole has been raised, different minerals are formed. The most characteristic minerals of this class are highly aluminous silicates, and in particular the pure silicates of alumina, which are rare or unknown in the igneous rocks. Since the amount of the different chemical constituents present in the sediments varies within wide limits, the minerals formed vary accordingly. In the following table is given a list of the principal ones: the first column shows the dominant chemical constituents of the original rock, the second column the minerals which result from the metamorphism of such a rock :—

Silica and alumina.	Andalusite (chiastolite), kyanite, sillimanite.
Silica, alumina and magnesia.	Cordierite, magnesia-garnet (pyrope), magnesia-mica (phlogopite).
Silica, alumina, and iron-protoxide.	Staurolite, iron-garnet (almandine), biotite.
Silica, alumina and alkalies.	Muscovite, felspar.

Thermal Metamorphism of Argillaceous Rocks.—When a mass of igneous rock is intruded into argillaceous sediments, clays, shales or slates, peculiar and characteristic effects are produced. As would naturally be expected, the action is most intense close to the contact, and becomes progressively less at greater distances therefrom. The minerals formed from the same original rock vary according to the temperature to which the rock has been subjected, so that an intrusion is often seen to be surrounded by a series of concentric rings of altered rock differing in character. Such a zone of contact alteration is called an *aureole*, and metamorphic aureoles are largely developed round many granite masses. As a rule the aureole around basic intrusions is much more limited in extent.

As a typical example of the metamorphism of argillaceous rocks we may take the case of the so-called Steigerschiefer in Alsace, described by Rosenbusch.[1] They have been altered by the intrusion of

[1] *Geol. Surv. of Alsace-Lorraine*, 1877.

the granite of Barr-Andlau, and the following zones of alteration are distinguishable :—

1. *Spotted Slate.*—In this stage the main mass of the rock has not undergone much alteration, but very abundant dark spots have been formed, which increase in size and number towards the granite. These spots appear to be accumulations of the black carbonaceous matter which is abundant in most rocks of this kind.

2. *Spotted Schist.*—In the next zone the spots are still abundant, while the ground-mass has also undergone some alteration, becoming harder, lighter in colour and more crystalline, and flakes of mica have been largely developed. The cleavage is gradually obliterated.

3. *Andalusite Schist.*—Still nearer the granite the spots completely disappear, and the rock is converted into a thoroughly crystalline aggregate of andalusite, mica, and quartz.

An interesting and somewhat similar case occurs in Britain, where the slates of the Devonian system are metamorphosed by the Dartmoor granite.[1] The first indication of alteration on approaching the granite is that the slates take on a greasy or soapy appearance. This begins to be manifest at a distance of some 300 or 400 yards from the granite. Still nearer spots appear, and in this case the spots are caused, not by aggregation of pigment, but rather by the absence of it. In this zone of spotted slate crystals of chiastolite also appear : apart from these the rock is not much altered. The next change is that the rocks become much more crystalline, with abundant andalusite and mica, still retaining their spots. This may be called a spotted mica-schist. Finally, close to the contact, the spots in some places are destroyed, and the rock becomes hard and compact. This may be described as a hornfels.

In the Skiddaw slates, around the Skiddaw granite, the relations are less definite, owing to the very variable lithological character of the sedimentary rocks. Black slates give rise especially to chiastolite, while in the flaggy and gritty beds cordierite and andalusite are dominant. The highest degree of alteration results in the formation of garnet and staurolite. Andalusite is abundant in the more aluminous bands, and a very characteristic feature is the formation of brown biotite. The chiastolite crystals appear in slates which have undergone so little general alteration that fossils, and especially graptolites, are still easily recognisable in them. Although the visible exposure of granite is very small, the aureole is of great size, having a diameter of nearly six miles : and it is probable that a large mass of granite underlies the whole area at a comparatively small depth.

Thermal Metamorphism of Arenaceous Rocks.—In cases where the texture of the original unaltered rocks is coarser than in those just

[1] Busz, *Neues Jahrbuch*, Beilage Band xiii., 1899, p. 90.

described, i.e. where they come under the designation of sandstones, grits, arkose, &c., the minerals produced are much the same as in the above list, but the texture of the metamorphic rocks is naturally coarser, so that they conveniently come under the designation of gneisses. Occurrences of such gneissose rocks as the result of thermal metamorphism have been described by Miss Gardiner[1] near New Galloway, and by Mr. Barrow[2] in the South-eastern Highlands. In the latter case it is possible to trace zones characterised by special minerals: staurolite, kyanite and sillimanite respectively: and these are believed to correspond to successively higher temperatures as the intrusion is approached. Many of the gneissose rocks of the Highlands contain abundantly the characteristic minerals of thermal metamorphism, and a large part of them seem to have assumed their present characters as the result of the intrusion of igneous rocks, either before or after intense dynamic metamorphism. It would be possible to multiply to any extent instances of thermal metamorphism of siliceous and argillaceous sediments, but the foregoing must suffice.

Thermal Metamorphism of Limestones.—In the case of calcareous rocks the chemical relations are somewhat simpler than in the sediments just described. When the limestone is pure, the only change which can be produced is recrystallisation, since the action of heat on calcium carbonate is a reversible one, and soon stops unless one of the products of dissociation is removed as fast as it is formed.

$$CaCO_3 \rightleftarrows CaO + CO_2$$

Under ordinary deep-seated conditions the carbon dioxide is not removed, and the calcium carbonate recrystallises as calcite, forming the granular crystalline rock known as marble.

When, however, the calcareous rock contains impurities, such as quartz grains and aluminous matter, the lime of the carbonate is able to enter into fresh combinations. The following are examples of changes which may occur.

$$CaCO_3 + SiO_2 = CaSiO_3 + CO_2$$

This leads to the formation of the simple lime-silicate wollastonite, with or without calcite, according to the proportions in which the constituents are present. The result is a wollastonite marble if the calcium carbonate is in excess, or a pure lime-silicate rock if enough silica is present to decompose all the calcium carbonate. If alumina occurs in addition, various alumino-silicates of lime may be formed, of which the chief are lime-garnet, idocrase and anorthite. Most limestones contain a little magnesia, and this gives rise to diopside or tremolite.

[1] *Q.J.G.S.*, 1890, p. 569. [2] *Q.J.G.S.*, 1893, p. 330.

One of the best descriptions of the thermal metamorphism of an impure limestone is that given by Harker and Marr[1] in the case of the Shap granite, in Westmorland. The Coniston limestone, of Upper Ordovician (Caradocian) age, is altered by the granite intrusion. It is a very impure argillaceous limestone, containing much silica and alumina, together with some magnesia. According to the local variations in its composition, it has given rise to a variety of lime-silicates, and may in different parts be described as a wollastonite-rock, an idocrase-garnet-rock, or a lime-felspar-rock. Similar changes are produced in some of the more calcareous beds of the Silurian in the same neighbourhood. Many of the impure limestones of the Highlands have also undergone far-reaching changes, and in a few cases scapolite has been produced as a result of contact-metamorphism.

Thermal Metamorphism of Dolomite-rock. Dedolomitization.—Most large masses of limestone are more or less converted into dolomite-rock, and when these are altered by contact-metamorphism some interesting phenomena are produced. Some of the beds of the Durness limestone in the Assynt district, which have been dolomitised, are metamorphosed by the plutonic complex of Cnoc-na-Sroine, and very similar phenomena are observed at Kilchrist, in Skye.[2] When the dolomite-rock is pure, or nearly so, the following change occurs–

$$\underset{\text{dolomite}}{CaMg(CO_3)_2} = \underset{\text{calcite}}{CaCO_3} + \underset{\text{periclase}}{MgO} + CO_2$$

The oxide of magnesia, however, is highly hygroscopic and soon undergoes hydration, forming brucite, $Mg(OH)_2$. The resulting rock, therefore, is a crystalline mixture of calcite and brucite, and may be called brucite-marble. A similar rock is known in the Tirol, and has there been called Pencatite.

When silica is present in the dolomite-rock, various silicates of lime and magnesia are formed. In the Durness limestone the silica is supplied by the cherty masses which occur there, and in other cases it occurs as detrital quartz grains. The minerals formed in these circumstances depend on the proportion of silica present, as follows: if there be only a little silica, so that the bases are in excess, the silica combines with the magnesia to form an orthosilicate of the olivine group, Mg_2SiO_4, forsterite, while the lime molecule forms calcite:

$$2\,CaMg(CO_3)_2 + SiO_2 = 2\,CaCO_3 + Mg_2SiO_4 + 2\,CO_2$$

The resulting crystalline rock is called forsterite-marble. If, however, silica is present in excess, the lime molecule also enters into the silicate.

[1] *Q.J.G.S.*, 1891, p. 266.

[2] *Struct. N.W. High.*, *Mem. Geol. Surv.*, 1907, p. 453; Teall, *G.M.*, 1903, p. 513; Harker, *Tert. Ign. Rocks of Skye*, 1904, p. 150.

forming diopside, $CaMgSi_2O_6$ or tremolite, $CaMg_3Si_4O_{12}$. Since the original rock usually contains calcite as well as dolomite, a crystalline aggregate of calcite and diopside or tremolite is formed: diopside-marble or tremolite-marble. The silicates thus formed are usually coloured greenish or grey by traces of iron, and frequently become serpentinised, yielding the mixture of serpentine and calcite known as ophicalcite.

General Effects of Thermal Metamorphism.—From the foregoing instances it will be seen that the effect of thermal metamorphism, when sufficiently intense, is to set up new minerals or to cause recrystallisation of existing minerals owing to an increase in the chemical activity of the constituents of the rocks affected. Besides these mineralogical changes, however, the physical characters of the rocks also undergo more or less alteration: they frequently become harder; stratification, jointing, lamination, cleavage and other structures are more or less completely effaced, and the colours are frequently altered. A common result of heating is the bleaching of highly coloured rocks, especially those whose colours are due to carbon or ferric oxide. Sometimes, on the other hand, shales and sandstones are reddened as if they had been heated in a furnace. These colour changes depend on an alteration in the state of oxidation of the colouring matter. Disintegration is rare, though cases have been observed: induration or hardening is much more common, and sometimes prismatic structures are set up, similar to these observed in some igneous rocks. In the Scotch coal-fields some of the coal-seams have been metamorphosed by sills of dolerite: the coal has often become columnar, while the dolerite has been bleached and converted into a light-coloured clay-like mass, probably by the reducing action of the carbon. In some localities coal has been converted by heat into a substance like coke, or into anthracite, or even graphite, owing to loss of volatile constituents. Thus it is evident that thermal metamorphism can produce important changes in the physical structure of the rocks into which the igneous rock is intruded, and in some cases, such as coal, an alteration of the total chemical composition may be brought about. The change just cited, however, is due to *loss* of some constituents, and involves no addition of material, as in the cases of chemical alteration to be hereafter considered (Metasomatism).

When the structure of many highly metamorphosed sedimentary rocks is considered, it is observed that, as a result of the metamorphism, a more or less distinct parallel arrangement of the constituents has been produced; this is sometimes conspicuous enough to be described as banding or foliation, thus bringing the rocks within the definition of schists or gneisses. This foliation is often seen to be quite independent of parallel structures which may have originally existed, and it usually appears to be developed parallel to the outer surface of the intrusion. It is usually only to be observed in the immediate neighbourhood of the igneous rock, and is probably due to crystallisation of minerals under the influence of stresses set up during intrusion, either by heat alone, or more probably by heat and pressure in conjunction. When minerals are crystallising under pressure, their growth will naturally take place most readily in a direction perpendicular to the pressure, and this in itself is sufficient to cause a parallel arrangement of elongated crystals, such as flakes of mica, or prisms of andalusite, staurolite, sillimanite, &c.

Thermal Metamorphism of Igneous Rocks.—The influence of high temperature on igneous rocks has not been so fully investigated as in the case of sediments, and it is not possible to treat the subject in such a systematic mannner. The amount of change produced depends upon a variety of circumstances, such as the original composition of the rock, the temperature to which it is raised, the duration of the heating, &c., just as in the case of the sediments; but in addition to these there is another factor of very great importance, it is the amount of alteration by weathering, &c., which the rock had undergone before being metamorphosed. It appears to be established that minerals which have been formed at a low temperature are more susceptible to alteration than those formed at a high temperature, so that the secondary minerals of decomposed igneous rocks are affected more easily than the minerals of fresh rocks which have been formed directly from the fused magma. This is especially noteworthy in the case of the hydrated minerals, zeolites, &c., which are frequently deposited in the vesicles of volcanic rocks. It is found that, on the whole, acid rocks undergo but slight alteration, unless decomposed, whereas basic rocks frequently show very considerable modifications. One of the most important cases is the metamorphism of sills and dykes of dolerite by granite intrusions, as in Cornwall, the Harz Mountains and elsewhere. The usual changes are conversion of augite into hornblende and recrystallisation of the felspar. Brown mica is also found, possibly owing to combination of the iron ores with the constituents of augite or its decomposition products. The augite-andesites of the Shap district show interesting changes near the granite. The augite of the ground-mass is converted into biotite, while the chloritic minerals of the vesicles have mostly recrystallised as hornblende or biotite.

The basalts of Skye have been metamorphosed by the later plutonic intrusions, and some interesting phenomena are described by Mr. Harker.[1] The changes observed in the body of the rock are almost

[1] *Tert. Ign. Rocks Skye*, p. 50.

identical with those in the Shap andesites: formation of hornblende and biotite from augite, and recrystallisation of felspar. These rocks are highly vesicular, the vesicles being filled chiefly with a great variety of minerals of the zeolite group. Under the influence of heat these have lost water and have recrystallised as felspars. Epidote and hornblende also occur.

The changes which have been set up in ashes and tuffs are of much the same character as in the corresponding lavas, but sometimes more intense, owing to the greater abundance of easily altered decomposition products. In some fine ashes spots are produced, and some of the minerals characteristic of metamorphosed sediments, such as andalusite and garnet, may be formed. The porphyritic felspars in both lavas and ashes are generally recrystallised as a mosaic of clear granules.

Dynamic Metamorphism

The movements which have affected the lithosphere have in most cases left clear traces of their action, and the sum-total of the phenomena thus occurring are comprised under the general heading of dynamic metamorphism. It is not always possible to discriminate clearly between the effects directly due to pressure and those due to the heat generated by friction, and, as we have already seen, there is evidence to show that the effects of thermal metamorphism are in some cases complicated by mechanical stresses directly due to the intrusive mass. Some of the mechanical effects of pressure acting on rocks have already been considered in the Introduction (folding, faulting, cleavage, foliation, &c.), and these do not here require description, so far as they relate to structures produced on a large scale. We are here concerned rather with the minuter structural and mineralogical changes which occur as a result of pressure: that is to say, with the petrography of the metamorphosed rocks.

The changes produced by stresses of compression and shearing may be divided into two heads: *physical* and *mineralogical* or *chemical*. The most conspicuous of the physical changes, at any rate to the naked eye, are cleavage, foliation and schistosity. These are, in part, simple rearrangements of the constituent particles of the rocks, adjustments to pressure; but they also in most cases involve a good deal of recrystallisation of existing minerals and formation of new minerals. On the whole, the new minerals formed are much the same as in thermal metamorphism, and it is scarcely necessary to give a list of them.

Crush Breccias and Crush Conglomerates.—Folding and faulting occurring in resistant rocks are often accompanied by a considerable amount of fracture on a comparatively small scale, by which the rocks are broken up into fragments, which may subsequently become cemented together again in the usual manner by deposition of cement &c., thus simulating ordinary clastic structures, such as breccias and conglomerates. They can, however, as a rule, be distinguished easily from true fragmentary rocks by the fact that the fragments are all of one kind, whereas clastic breccias and conglomerates are almost always *polygenetic*, being composed of fragments of different kinds of rock. Sometimes the broken masses remain angular, forming a crush breccia: this is particularly common along fault-planes, where the fissure is frequently filled by a mass of angular fragments of the country rock, the so-called fault-breccia. In other cases, however, there has been so much rolling and crushing that angles become rounded off, and the whole simulates very closely the appearance of a bed of water-worn pebbles, a true sedimentary conglomerate.

Crush-conglomerates have been described in many localities in the British Isles. An excellent example is to be seen in the Isle of Man, where the Manx slates have undergone intense folding and compression. Here fragments of gritty beds of all sizes are found embedded in an argillaceous matrix, representing original shales.[1] Again, in Argyllshire, Mr. Hill[2] has described somewhat similar structures resulting from the folding together and subsequent shearing of beds of very different hardness, viz. epidiorite and limestone. The lenticles thus produced are rolled out and flattened, and often simulate closely the Highland Boulder-bed, a true clastic conglomerate, which has also undergone dynamic metamorphism to a high degree. This latter, however, is distinguished by the fact that it is of polygenetic origin, containing pebbles of granite and other foreign rocks. Crush conglomerates also occur on a large scale in the Lower Palæozoic rocks of Cornwall, especially in the Mylor series,[3] and here it is clearly evident that the rapid alternation of beds of different material and hardness is an important factor in this type of deformation. A somewhat similar case in the Ilfracombe beds in North Devon has been described by Dr. Marr.[4] Beds of limestone and grit, intercalated in an argillaceous series, have been thrown into sharp sigmoidal folds, in which the middle limb is often replaced by a thrust-plane. The 'eyes' thus produced eventually form flattened lenticular patches of hard rock interbedded with the softer and more compressible slate. The final result is a schist with apparent false bedding. The apparent bedding is, however, in no way related to the original stratification, but depends entirely on the direction of pressure.

[1] Lamplugh, 'Geology of the Isle of Man,' *Mem. Geol. Surv.*, 1903, pp. 55, 70.

[2] *Q.J.G.S.*, 1901, p. 313.

[3] Hill, *Summ. Progr. Geol. Surv.*, 1899, p. 92.

[4] *Geol. Mag.*, 1888, p. 218.

Lenticular or 'Eyed' Structure.—When a mass of rock containing elements of varying hardness, or crystals of conspicuously large size, is subjected to crushing stresses, the softer or smaller fragments are frequently rearranged in streaks with approximately parallel structure, which show a strong tendency to flow round the larger or more resistant masses: these in their turn are often more or less rounded off or flattened, so that the whole assumes a sort of lenticular appearance, which may be called *eyed structure* ('Augen Struktur'). This is very apparent in many crushed porphyritic rocks, forming *eyed gneiss* or *augen gneiss.* This type of structure passes by every gradation into ordinary foliation and schistosity.

Structural Changes in Minerals.—On a smaller scale than the phenomena just described are the structural changes which result from the crushing of crystals. These changes are mostly to be observed in microscopic sections, and are connected with strains of compression and recrystallisation, which frequently involve addition of material to existing crystals, along lines of least resistance. When examined in polarised light, the crystals of crushed rocks frequently show an alteration of their optical properties: for example, the extinction of doubly refracting crystals loses its sharpness and becomes uncertain, waves of extinction passing over the crystal as it is rotated. Again, crystals of minerals, such as garnet, which are normally singly refracting, frequently show double refraction. Also secondary twinning may be produced by strain, probably owing to a slipping of the molecules; and original twin lamellæ, cleavages and other linear parallel structures may become bent and distorted. In a further stage of deformation the crystals are cracked or actually broken. Such broken crystals frequently undergo more or less complete recrystallisation, so that the place of one large original crystal is occupied by a mosaic of smaller crystals of the same substance. In some cases of intense crushing, as for example in the neighbourhood of great thrust-planes, the shearing and grinding action has been so strong that an original coarsely crystalline rock is ground down to a paste of exceedingly fine texture, known as *Mylonite.* This name was first applied by Lapworth to the crushed rocks which have been affected by the movement of the great thrust-planes of the North-west Highlands. When the crushing has been less intense a structure is produced which is known as granulitic, and the resulting rock is a *granulite.* Here the original crystals are destroyed and the material is recrystallised as an even-grained mosaic of small crystals of the same or different minerals, often with conspicuous parallel orientation and banding. This is one form of foliation, which does not, however, imply the existence of actual planes of discontinuity, but merely a parallel arrangement of bands of minerals of varying composition and colour. This structure is very common in originally coarse-textured igneous rocks which have been subjected to shearing strains during dynamic metamorphism.

Dynamic Metamorphism of Sediments.—The effects of dynamic metamorphism in sedimentary rocks depend to a very large extent upon the original texture of the rock. If this texture is fine the result is cleavage of a greater or less degree of perfection. Cleavage is always accompanied by a certain amount of recrystallisation and production of new minerals, and in some cases the rock appears to have been almost entirely reconstituted. Usually the characteristic mineralogical change is the formation of mica, and minerals of the chlorite group. When much quartz was originally present it is, as a rule, recrystallised as a mosaic of minute grains, while other minerals, such as garnet, are often formed. When the resulting rock is highly crystalline and glossy in appearance, it is often spoken of as *phyllite*. This may be regarded as a more advanced stage of metamorphism than ordinary slate, and such rocks are as a matter of fact microcrystalline mica-schists.

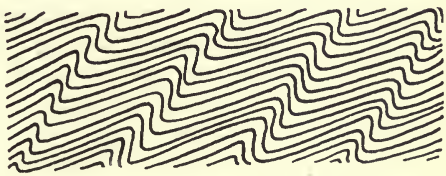


Fig. 87.—Diagram to illustrate False Cleavage.

False Cleavage.—Rocks of fine texture often undergo a good deal of crumpling or folding on a minute scale, and this may give rise to a peculiar structure known as *false cleavage* (Fig. 87). When a well-bedded rock is subjected to pressure in a direction making a high angle with the original bedding, small sharp folds are produced, often unsymmetrical or overfolded, and the middle limbs of these small folds are planes of special weakness along which the rock has a tendency to split. False cleavage, or *strain-slip cleavage* as it is sometimes termed, differs from true cleavage in the fact that splitting is only possible along certain planes, as can be seen from the diagram, and the rock cannot be split up into indefinitely thin layers, as in true cleavage. This structure may be observed of almost any degree of magnitude, and is very common, on an almost microscopic scale, in slates and schists. The dynamic metamorphism of fine-textured rocks is always, as before stated, accompanied by formation of new minerals, the character of which depends on the composition of the original rock. Quartzose sediments, such as grit and sandstone, are converted into quartzites, which show a strong resemblance to the quartzites of thermal metamorphism, though, as would naturally be expected, optical anomalies, such as strain-shadows, are still more strongly marked. When the sandstone is impure, new minerals are formed, of much the same character as in thermal metamorphism; but in addition to this, a marked type of foliation is commonly produced, so that the altered rocks are *gneisses*, which in many cases are difficult to distinguish from gneisses of igneous origin. However, since the intensity of dynamic metamorphism is not everywhere the same, it is frequently possible to trace these gneisses laterally into more or less unaltered clastic sediments, as has been done by Cunningham-Craig in the case of some of the rocks of the Southern Highlands.

Speaking generally, we may say that, when sedimentary rocks are subjected to pressure, the changes induced are somewhat as follows. Very fine-grained rocks produce slates when not much recrystallised, and phyllites or schists when highly crystalline; the term schist is a somewhat vague one, and is most commonly used to express rocks with a glossy or micaceous appearance, often strongly fissile, and also frequently more or less contorted, so that they do not split so evenly as slates. Coarse-grained sediments, on the other hand, produce gneisses and quartzites. It is impossible, however, to give any strict definition separating gneisses from schists. The two types pass into each other by insensible gradations. It may also be remarked here that most of the foregoing statements apply to the fragmentary rocks of volcanic origin, so far, at any rate, as structures are concerned. Many of our best roofing slates have been formed by cleavage of fine ashes, as in North Wales; while in the green slates of Cumberland the original texture was comparatively coarse, and large fragments, up to one or two inches in diameter, are still recognisable on the cleaved surfaces (e.g. the so-called 'Rain-spot slate' of Borrowdale).

Dynamic Metamorphism of Igneous Rocks.—In this class of rocks as well as in sediments pressure gives rise to parallel structures, accompanied by more or less mineralogical change, and the resulting rocks are known as gneisses, schists, &c., according to their general appearance and texture. The degree of mineralogical change which occurs in them varies a good deal in accordance with their original composition, and the amount of alteration which the minerals have previously undergone. The minerals of the acid rocks do not seem to undergo much alteration; but it is probable that in most cases there has been in reality a good deal of molecular rearrangement owing to the pressure: the minerals finally formed are of the same general character as those originally present, since the minerals of the acid rocks as a whole are those which are stable under conditions of high pressure and moderate temperature. Original pyroxene is often converted into amphibole, whereas on the other hand hornblende sometimes recrystallises as augite. The reason for this variability of behaviour is not clear, but the latter change probably takes place at a higher temperature. Quartz and the felspars are more or less recrystallised, and show strain-shadows, granulitisation and other structures previously described. In the basic rocks, on the other hand, more far-reaching changes are set up, involving a good deal of molecular and chemical reconstruction. Rocks originally rich in olivine are converted into schistose aggregates of actinolite, anthophyllite and talc. Massive rocks such as dolerite and basalt undergo an interesting series of changes, of which the final result is a hornblende schist or amphibolite. A special case, that of the Scourie dyke in Sutherland, has been exhaustively described by Dr. Teall.[1] The first stage of alteration is the conversion of the original augite into actinolitic hornblende (uralitisation) : the rock in this state may be described as an epidiorite. As a result of stronger pressure the felspar is also recrystallised, and the final result is a hornblende-schist.

Pneumatolytic Metamorphism (Metasomatism).—The phenomena comprised under this designation differ from those hitherto dealt with in the fact that addition of material takes place from external sources. By this means new elements are often introduced, and minerals formed of an altogether peculiar character. The most important case of alteration of this kind is that which takes place in connexion with pneumatolysis of igneous rocks. As already explained, certain plutonic intrusions are accompanied by strongly marked gas-action, which produces noteworthy effects on the igneous rocks themselves; and the influence of these vapours of high chemical activity naturally extends outwards into the surrounding rocks. The nature of the changes brought about depend on two factors: the character of the gases, and the composition of the rocks themselves. It has already been pointed out that pneumatolysis is much more conspicuous in the case of acid magmas than in basic ones, and it is most strongly marked in the granites. As an example, the phenomena accompanying the intrusion of some of the Cornish granites, especially the Land's End mass, may be taken. Here there are to be seen fine examples of contact-metamorphism of more or less normal type, resulting in conspicuously spotted rocks, with andalusite, cordierite, secondary mica and other minerals of normal thermal metamorphism. But in addition to these there are various special minerals containing fluorine, boron and other elements characteristic of pneumatolysis. In many cases impure arenaceous and argillaceous rocks, grits, slates, &c., have been converted into aggregates of quartz and tourmaline, and yet still show indications of bedding or cleavage: they are conveniently spoken of as tourmaline-schists. These are found close to the granite only. The process of formation of these tourmaline-schists is exactly parallel to that of schorl-rock (see p. 252). The tourmaline arises partly by replacement of biotite or chlorite and felspar, and

[1] Teall, *Q.J.G.S.*, vol. xli., 1885, p. 133.

partly by deposit from aqueous solution. Sometimes abundant secondary muscovite is formed in the sedimentary rock, and this may be compared to greisening in the granite.[1]

Of special interest are the effects produced by gas-action on impure calcareous rocks.[2] The characteristic minerals here found, which do not occur in ordinary thermal metamorphism, are as follows: axinite, green pyroxene, fluor-spar, tourmaline, zinc-blende, yellow garnet, talc. Besides these, there occur idocrase, actinolite, epidote and other minerals similar to those formed by thermal metamorphism in other localities. Another mineral which is sometimes formed under similar conditions is datolite, a compound of calcium and boron.

[1] Reid and Flett, 'The Geology of the Land's End District,' *Mem. Geol. Surv.*, 1907, p. 21.

[2] Barrow and Thomas, *Min. Mag.*, vol. xv., 1908, p. 113.

CHAPTER XV

ORE DEPOSITS

The geology of ore deposits is in reality nothing but the application of certain principles of structural geology and petrology to the study of a class of substances that happen to possess commercial value as sources of the metals employed for various technical and industrial purposes. The accepted definition of an ore is that it is a mineral or rock containing one or more metals in payable quantities; such a definition can obviously include deposits formed in geologically very different ways; hence the classification and generalised treatment of this group presents special difficulties. To the practical man, the miner and the engineer, the points of importance are the metal-content of the deposit, its form and its extent. Hence the earlier attempts at classification were mostly based on form; it is only of late years that the principle of genetic relationship has been introduced into the study of ore deposits, and the subject is still in process of development.

Primary and Secondary Ore Deposits.—Whatever scheme of classification may be adopted, it is necessary to draw a clear distinction between the two main classes of ore deposits, primary and secondary, which differ fundamentally in their origin and geological relations. The primary ore deposits are those in which the metalliferous minerals have been formed in the positions where they are now found, whereas the secondary ore deposits contain ore minerals formed elsewhere, and transported to their present position by processes of physical geology. In point of fact the distinction is analogous to that between igneous und sedimentary rocks. In the former category come most of the important ores of copper, lead, zinc, silver, antimony, bismuth, and many others, while the secondary group includes gold, tin, platinum, and a few more. Many of the important iron ores, together with a number of compounds of other metals, belong rather to the class of metamorphic and metasomatic rocks, some being directly due to the influence of igneous intrusions, while others are due to alterations in rocks by solutions at the ordinary temperature and pressure. It must, of course, be understood that many metals belong to more than one category; for example, it is the working of the agents of denudation and transport on *primary* ores of gold, platinum, and tin that gives rise to the secondary deposits of those metals, while ores of iron, for example, originate in almost every way that is geologically possible: igneous, sedimentary, metamorphic, and metasomatic. Hence it appears that the subject is complex and difficult to deal with in a satisfactory manner. Every classification, on whatever basis, must be more or less in the nature of a compromise.

Morphological Classification.—Among the older classifications, based solely on external form, that proposed by Von Cotta[1] is the simplest and most useful; it is as follows:—

I. Deposits of Regular Form—
 1. Beds.
 2. Veins.
II. Deposits of Irregular Form—
 1. Masses.
 2. Impregnations.

This scheme almost explains itself. The term 'beds' is to be taken as including all the stratified deposits, whether primary or secondary; the second group, 'veins,' includes all the varieties of dykes, lodes, and veins traversing rocks irrespective of direction, as afterwards explained. With regard to irregular masses, it is obviously impossible to generalise, but certain more or less definite types can be recognised. These are described in a later section (see p. 279). Impregnations (now often called disseminations) may also obviously be of any form whatever, and usually do not possess well-defined boundaries.

Genetic Classification.—In recent times many different schemes have been proposed for a truly scientific classification of ore deposits, based on a consideration of their mode of origin.[2] It is now generally recognised that the study of ore deposits is a branch of petrology, and that their formation can be referred to one or other of the ordinary categories of rock-formation, igneous, metamorphic, or sedimentary. Most of the secondary deposits are clearly sedimentary, while many of the primary ores are as clearly of igneous origin; there still remain, however, a certain number of doubtful cases that require further investigation. It was at one time generally believed that most, if not all, of the primary ores were formed by deposition from water at or near atmospheric temperature and pressure; that is to say, by the meteoric ground-water of the outer layers of the earth's crust. Further experience clearly showed, however, that some ores were formed at high temperatures and pressures by igneous processes, and of late the

[1] *Die Lehre von den Erzlagerstätten*, 1859.

[2] For a detailed discussion of this subject see Thomas and MacAlister, *The Geology of Ore Deposits*. Second Impression. London: Edward Arnold, 1920.

tendency has been to extend this to the great majority of cases. It is possible that this idea has been carried too far, but in a vast number of instances it is certain that the ores are of igneous origin. Besides these there are deposits commonly classed as due to contact and replacement. The contact deposits are essentially metamorphic in their origin, being due to the action of igneous intrusions, while the replacement deposits naturally come within the category of metasomatism, as before defined; many of the ore-bodies placed in this class are obviously due to transfer to metallic material from intrusions to the surrounding rocks. It is doubtful whether any hard-and-fast line can be drawn between these classes, since in most of the contact deposits there has evidently been addition of metallic elements to the surrounding rocks.

Primary Ore Deposits.—In this category are included, in the first place, all the ores which are known to be of direct igneous origin, and the contact and replacement bodies which are due to the intrusion of igneous rocks, or which in some cases accompany the extrusion of lavas. The origin of such ores is essentially part of the process of differentiation of igneous magmas spoken of on p. 248, which is closely bound up with the phenomena known as pneumatolysis. When an igneous magma is undergoing differentiation, its constituents separate in a certain definite order, depending on their solubility in the magma and the amount of flux present. Ore minerals behave very variously in this respect, but it may be stated in general terms that they usually crystallise either very early or very late, according to whether the metal does or does not form volatile compounds; thus nickel, chromium, and platinum seem to crystallise at an early stage, while tin, lead, and zinc belong to the very latest phases. One consequence of the latter type of behaviour is that deposits of tin and its companions tend to get mixed up with the processes known as pneumatolysis, which also belong to the latest phases of the cooling of an intrusion. Hence some authors have tried to classify primary metallic deposits into *magmatic*, *pneumatolytic*, and *hydrothermal*. This division is arbitrary, since no hard-and-fast lines can be drawn, but it is useful as a working basis. Under the heading of magmatic deposits are generally understood those compounds of the useful metals which are actually found as original constituents within the igneous rock, either scattered uniformly through its mass or segregated into masses in some particular part of it. Such segregation is due to some type of differentiation, either sinking of heavy crystals, diffusion to a cooling surface, or separation of immiscible liquids, as in the case of pig-iron and slag. All these causes are probably operative. Examples of such masses are afforded by some of the iron ores of Sweden and Norway and of the State of New York, the nickel-bearing sulphides of Sudbury in Canada, and the platinum of the Urals.

Vein Deposits.—More widespread than the foregoing are the ore deposits, which take the form of tabular masses or sheets, either vertical or inclined like dykes, and more rarely horizontal, like sills. As a matter of fact, they are very closely related to dykes and sills by origin as well as by form. They may be described as due to the infilling of fissures in the rock by material of igneous, pneumatolytic, or hydrothermal origin, or even laid down from solutions at normal temperatures. During the cooling of igneous intrusions there is commonly a tendency for the metallic constituents to concentrate in the last residues of the magma, so that they become associated with the material of the pegmatites and aplites that are intruded during the latest stages of the cooling, and also with the vapours and solutions that give rise to the secondary changes in rocks and minerals known as pneumatolysis, while some of them pass out from the intrusion in the hot siliceous solutions that form quartz veins. As a matter of fact, all these stages are parts of one continuous process. Many pegmatites, consisting of, say, quartz, felspar, and mica in and near a granite, have been traced laterally without definite break into pure quartz veins, the change simply being a gradual diminution of felspar and mica when followed outwards from the granite. Metallic minerals are often present throughout such a vein, or they also may diminish in amount in the same way. Veins formed in this manner often contain an extraordinary variety of minerals, both metallic and otherwise. The valueless part is generally called the *gangue*, as opposed to the valuable part, or *ore*. In many instances

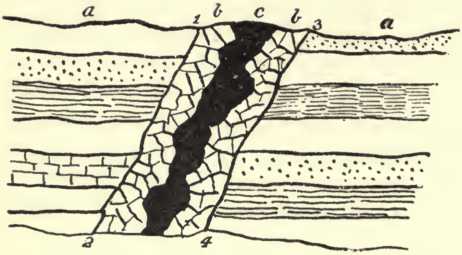


FIG. 88.—MINERAL VEIN OCCUPYING FAULT-FISSURE IN STRATIFIED ROCKS.

aa, Sedimentary rocks, the 'country'; *bb*, Veinstone or gangue; *c*, Metallic ore; 1, 2, Hanging-wall; 3, 4, Foot-wall.

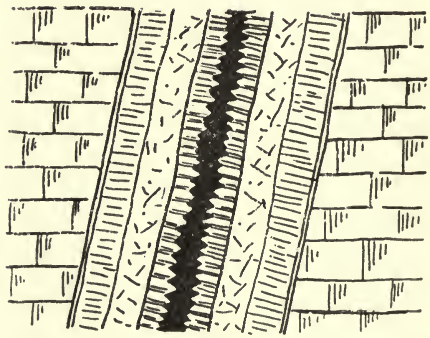


FIG. 89.—COMPOUND MINERAL VEIN.

it is easy to show that the filling of a vein has taken place in two or more stages (see Fig. 89), the different minerals being deposited in a definite order, and sometimes it can be proved that after filling the vein has again been opened by earth movements and another lot of minerals deposited. This may be repeated any number of times. When, as is often the case, the vein occupies a fault-fissure, it may be more or less completely filled by fault breccia, with ore and gangue deposited in the interstices. Such brecciated lodes are common. In some parts of the world, especially in Africa, veins are often called *reefs.*

When a vein is vertical its position is defined by its *strike*, just as in the case of a vertical bed. An inclined vein is now commonly defined by its strike and dip or underlie, which are measured as before described (see p. 16). Occasionally instead of dip the term *hade*, the complement of the dip, is employed, but this is rapidly going out of use. In inclined veins the bounding surface that lies uppermost is called the *hanging wall*, that below the *footwall.* Since veins are often faults or lie along the contact of two rocks, these are often different. When followed by mining to a great depth the dip of a vein often changes, and may vary on either side of the vertical. The dips are commonly at high angles, not often less than 50 degrees. In any given district veins often follow more or less closely certain definite directions, determined by faults or major joints in the rocks, and one set of fault-veins may intersect and shift another set, thus giving rise to complicated structural problems in determining the proper direction in which to drive to pick up the continuation of a faulted vein.

Sometimes, however, mineral deposits of this character are less definite than just described. When the mineralising solutions are traversing the rocks they may not be able to find clean-cut open channels for their passage, but may be forced to penetrate along extremely narrow cracks or through fractured zones in the rocks, such as shatter-belts. The ore minerals may then be deposited in a finely divided condition along an ill-defined belt of rock without definite walls. Such zones of deposition and ore-formation often extend outwards for some distance on either side of a narrow crack, which is then called a *leader*, and the whole mineralised band may then be called a *lode.* This term, however, is not very precise, since it is often used for well-defined veins with a distinct filling; such lodes cannot be clearly distinguished from brecciated veins. Very small veins are often spoken of as stringers, and a mass of rock permeated by great numbers of small veins or stringers is called a *stockwork* (Fig. 90). Sometimes the veins in a stockwork are so numerous and close-set that the whole mass forms a payable ore, and the ore-body then differs little in practice from a dissemination.

Examples of mineral deposits of the foregoing types are innumerable in almost all parts of the world. An admirable example is afforded by the tin-copper lodes of Cornwall, which contain copper in their upper parts and tin below (Fig. 91). Some of these—as, for example, at Dolcoath Mine—have been worked to a depth of 3,000 feet. Here, as in so many other places, the mineralisation is accompanied by pneumatolysis, and the lodes are associated with great quantities of tourmaline, topaz, fluorspar, and other minerals rich in fluorine and boron. Tin, with tungsten, uranium, and other metals, is found in greisens, while the later lode-fillings include compounds of lead, zinc, iron, antimony, bismuth, and other metals. Gold-quartz veins are very common in many parts of the world, while silver-cobalt veins in Canada, silver-tin veins in Bolivia, tin-tungsten veins in Lower Burma, all give rise to important mining industries. Some of the most important copper deposits of the world are found as lodes and veins in connection with igneous intrusions, as in Montana, Arizona, and other parts

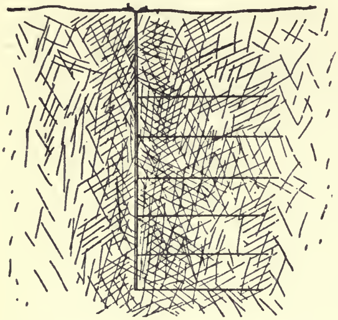


FIG. 90.—STOCKWORK.

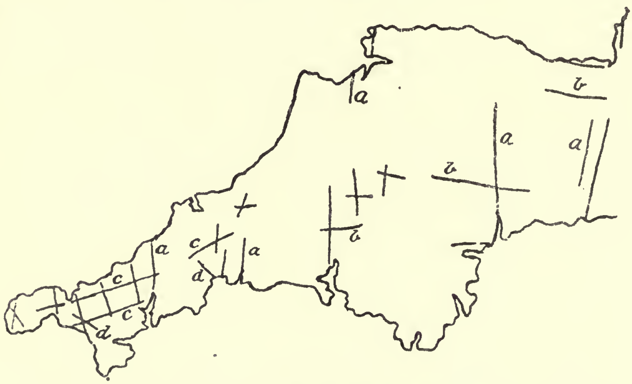


FIG. 91.—MAP SHOWING THE LODES OF DEVON AND CORNWALL. (After De la Beche.)

The set *a*, *a*, running north and south, contain lead and zinc; the sets *b*, *c*, *d*, striking in general in an east and west direction contain the chief copper and tin ores, and are shifted by the set, *a*, being of earlier age.

of the United States, and in the Andes of South America. Another remarkable type of ore deposit of pneumatolytic origin is afforded by the 'pipes' of Queensland and New South Wales, which yield much tin, bismuth, tungsten, and molybdenum. These are cylindrical masses of quartz, usually from 10 to 40 feet in diameter, often containing also felspar and mica, with the metallic minerals arranged in zones. They seem to be formed by the passage of mineralising gases during the pneumatolytic phase of cooling, and their position appears to be determined largely by joints.

Cavity Fillings.—Closely related to the true vein deposits are certain less regular ore-bodies formed by deposition of material in pre-existing cavities in rocks. This type is best illustrated by the lead-zinc ores found in the Carboniferous Limestone of many parts of Great Britain. The occurrence in this rock of open joints and cavities of all shapes, ranging up to large caverns, has already been described (see p. 62). These cavities are frequently filled by masses of galena and zinc-blende, with calcite, barytes, fluorspar, and other gangue minerals. It was at one time generally believed that these minerals were deposited by meteoric water circulating through the rocks at the ordinary temperature, in contrast to the high temperature veins before described; but there are certain difficulties in the way of this theory. In the first place, it is hard to see where the metals came from on this supposition; it is known that ground-water does not penetrate far below the surface, since most very deep mines are dry. Hence the metals must have been extracted from the surrounding rocks and concentrated in the cavities (Lateral Secretion theory). Secondly, the abundance of fluor-spar certainly suggests a connection with igneous magmas. On these grounds it is now generally believed that these deposits also are of magmatic origin, deposited by ascending thermal waters from underlying igneous rocks. In this connection it is significant that in Cornwall the later veins contain lead and zinc, while there can be no doubt that they are due to the same primary cause as the earlier tin-copper veins.

The form of these ore-bodies in the limestones is obviously controlled by the shape of the cavities. Fillings of vertical joints form veins, the *rakes* of the Derbyshire miners; deposits along bedding planes are called *flats*, while more or less cylindrical masses formed at the intersection of two vertical joints are *pipes*. These are essentially filled-up potholes. Various irregular masses of indeterminate form are often called *bunches* and *masses*.

When ores are deposited in highly folded rocks, they often tend to accumulate specially in the arches of anticlines and to a less extent in the troughs of synclines, owing to the existence there of places of special weakness or even open spaces (see Fig. 92). The best example of this is afforded by the gold-bearing saddle-reefs of Bendigo in Victoria, which have yielded an immense amount of gold.

Replacement Deposits.—These occur most commonly in limestone, though they are sometimes found in other rocks. One of the most important examples is afforded by the great iron-ore deposits of Cumberland and the Furness district of Lancashire. Here the Carboniferous Limestone was originally covered unconformably by the very ferruginous strata of the Permian and Trias. Water percolating through these passed down into limestone below, carrying iron in solution. When this came in contact with the calcium carbonate of the limestone, the iron displaced the lime of the carbonate, probably first forming ferrous carbonate, which was later oxidised to ferric oxide or hæmatite (Fig. 93). These replacement bodies are usually of very irregular shape and often of great size; the Hodbarrow Mine on the Duddon estuary, which works a single ore-body of this kind, has an annual output of about 400,000 tons of ore, averaging about 54 per cent. of metallic iron. The same effect is seen on a smaller scale in the Carboniferous Limestone of South Wales (Fig. 94) and in some of the Devonian limestones of Devon. The highly important iron ores of Bilbao, in Northern Spain, are due to the metasomatic replacement of a Cretaceous limestone equivalent in age to the Gault. Very numerous examples of replacement and metasomatic ore-bodies have been described in many parts of the world, and some of them are of great practical importance. Where definite mineral veins traverse limestone, such bodies are often found extending outwards from the veins and thus extending their workable size. When the veins traverse an alternation of limestone beds with more resistant strata the width of the payable portion is often much greater in the limestones.

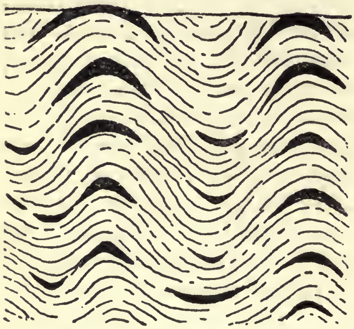


FIG. 92.—SADDLE-REEFS.

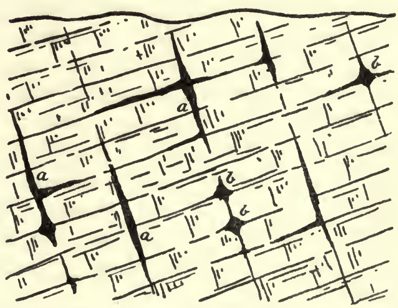


FIG. 93.—GASH VEINS, OR PIPES, AND BUNCHES IN LIMESTONE.

a, Gash veins, or pipes ; *b*, Bunches.

Sedimentary Ore Deposits.—In this group are included all the rocks and unconsolidated deposits of sedimentary origin which contain sufficient metal to be of value as workable ores. There are two principal categories of these—(*a*) the alluvial deposits; (*b*) the stratified iron ores. Some residual deposits are also of commercial value.

The term 'alluvium' is often interpreted by mining geologists in a rather broad sense to include besides true alluvium some of the deposits included under the heading of colluvial in the table on p. 75. Many metallic minerals are both very stable and very heavy, hence tending to survive and accumulate in superficial deposits. Such, for example, are gold, tinstone, and platinum, which are often found in quantity either on or just below the outcrop of the lode or other ore body, or in transported sands and gravels formed by the ordinary geological processes in rivers, lakes, or in the sea. Owing to their high density there is often a natural sorting and concentration of such material by stream or wave action. As examples we may mention the gold gravels of Australia, California, and the Klondike; the tin gravels of Cornwall, the Malay States, and Nigeria; and the platinum gravels of the Urals.

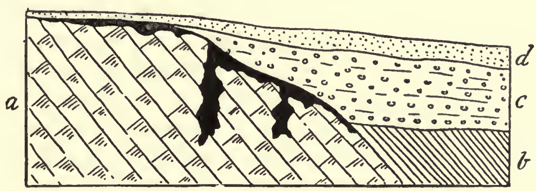


Fig. 94.—Hæmatite replacing Limestone in the Carboniferous Limestone Series, South Wales.

***a*, Carboniferous limestone ; *b*, Shale of the Millstone Grit ; *c*, Trias ; *d*, Superficial deposits.**

Many gem-stones also tend to occur in a similar way, as diamonds in Brazil and the Vaal River, rubies and sapphires in Ceylon. In many places around the Pacific differential sorting by wave action has formed great beds of black sand, composed of magnetite and ilmenite, often with gold, and in the same way monazite sands have been formed on the coasts of Brazil and Travancore; this is the chief source of thorium for incandescent gas-mantles. In Australia and California gravels of Tertiary age, often covered by later lava-flows, have been worked extensively for gold.

Many of the most important and valuable iron ores of the world are stratified sedimentary rocks of different ages. The simplest type is the black-band and clay-band ironstone of the British Coal Measures, which appear to be in origin exactly analogous to the modern bog-iron-ore and lake-ore described on p. 148. More difficult to decide is the question of the origin of many examples of oolitic iron ore, such as those of the Jurassic system in Britain and Lorraine, the Clinton

(Silurian) ores of the United States, and the Wabana ore (Ordovician) of Newfoundland. In many of their characters all these are very like oolitic limestones, but they consist mainly of iron oxide, carbonate, and silicate. The main point at issue is whether these beds were deposited as iron compounds, or whether their present composition is due to a metasomatic replacement of lime by iron. This question is still undecided. For a further discussion see p. 147.

Among the truly residual ore-yielding deposits, the most important is laterite (see p. 77). In the typical laterite deposits of India three chief types can be recognised, connected by all intermediate gradations; these three types are characterised by iron, alumina, and manganese respectively. Some Indian laterites form quite good ores of iron and manganese, but the most important is undoubtedly the aluminous variety, which forms bauxite, the only practical ore of aluminium. Similar deposits of earlier date are found in the south of France and in the north-east of Ireland. Laterite of all types has a very wide distribution in the tropics, and is often sufficiently aluminous to be called bauxite.

Iron Ores in Crystalline Schists.—In many areas of gneissose and schistose rocks iron-bearing minerals are disseminated in large quantities, and sometimes they are sufficiently concentrated to be of workable value. Some of these are certainly magmatic concentrations, such as the Swedish ores already mentioned; others are undoubtedly of metamorphic origin, where the iron-content of originally ferruginous sediments has been recrystallised by heat and pressure as magnetite or hæmatite. Some of these iron-bearing deposits, formerly considered of too low grade to be workable, can now be concentrated by magnetic separators to high-grade products, as in the Sydvaranger district, Northern Norway, where the annual output of concentrates is about 600,000 tons.

The iron-bearing rocks of the Lake Superior region are of a peculiar type, and their origin is not yet fully understood. There is no doubt that they were originally sediments, and it is now generally held that the iron is a primary constituent, present at the time of formation of the rock and laid down as a precipitate from sea-water, probably as green ferrous silicate, along with colloidal silica, thus forming a ferruginous chert. This primary rock is not usually rich enough in iron to form an ore, but in places the iron has undergone natural concentration and enrichment, generally as hæmatite, sometimes as magnetite. These iron-bearing rocks of the Marquette, Menominee, Penokee, Mesabi, Gogebic, Cuyuna, and Vermilion ranges support the largest iron-mining industry of the world, the annual output being now about 75,000,000 tons.

Secondary Changes in Ore Deposits.—Most of the primary ores of the magmatic, pneumatolytic, and hydrothermal groups are sulphides, only a few primary ore minerals containing oxygen. So long as these are not affected by weathering they remain unaltered, but when owing to denudation they are brought within the reach of superficial geological agencies, chemical changes begin, mainly by the action of ground-water containing carbon dioxide and oxygen. Thus the primary sulphides are oxidised to sulphates, carbonates, oxides, hydrates, and a large variety of other secondary minerals, some of which are soluble in water. These metallic solutions tend to travel downwards till they reach the level of ground-water, where reducing conditions prevail and the dissolved substances are again precipitated, either as secondary sulphides, often of complex composition, or as native metals. Thus at the bottom of the weathered zone is found a richly mineralised layer, called the zone of secondary enrichment. To take the simplest case, that of a lode of copper pyrites ($CuFeS_2$): near the surface this is decomposed, forming insoluble iron hydrate, which remains in place, and soluble copper compounds, which partly remain in the oxidised zone as green and blue copper carbonates, and partly pass down to be reprecipitated as various copper-bearing sulphides such as chalcocite, and complex sulphides of copper and other metals; as cuprite, which is cuprous oxide; or as the native metal. Below this rich zone the unaltered primary sulphide is found. In a similar way sulphides of lead and zinc are altered near the surface to sulphates, carbonates, and other oxidised compounds. Silver and gold are often concentrated in the zone of secondary enrichment from the very small amounts present in the primary ore; thus rich deposits, or bonanzas, may be derived from original low grade primary ores.

In a very similar way the outcrops and oxidised parts of beds of iron-ore are often much richer than the unweathered portion below. In the case of iron-ores, however, the oxidised iron compounds are mostly insoluble, and the concentration is largely due to removal of other more soluble substances, especially lime, from the weathered parts. The enrichment of the Lake Superior ores, however, seems to have been brought about by solution of the iron, with subsequent deposition in basins formed by the folding of the sediments, some of which are impervious to solutions.

The Mineral Composition of Ore Deposits.—The total number of minerals which can be exploited as sources of metals is very great, and it is impossible to give here anything like a complete list of them. For this systematic works on the subject must be consulted. It may be well, however, to give a very brief résumé of the principal sources of the commoner metals without entering into any detail.

It is necessary to draw a clear distinction between the metalliferous portion of the deposit, the *ore minerals* in the narrow sense, and the worthless associates or *gangue*. Some of the gangue minerals may have a value for special purposes, though not as sources of metals. The most common gangue minerals are quartz, calcite, dolomite, barytes, and fluor-spar. Chalybite (siderite) is not uncommon in mineral veins, and may be regarded either as gangue or ore, according to whether it is utilised as an iron-ore or thrown away as worthless. This depends mainly on questions of transport and markets. Barytes is of value in the manufacture of paint, and fluor-spar is employed as a flux in certain metallurgical processes.

The principal metals of value, in the commercial sense, occurring in true ore deposits are as follows: gold, silver, platinum, mercury, copper, tin, tungsten, lead, zinc, antimony, arsenic, bismuth, nickel, cobalt, manganese, and iron. Of these gold takes the lead in cash value, iron coming next, if we reckon the price at the mine, though the value of the manufactured iron far exceeds that of the gold.

Gold occurs either as the native metal, or as telluride, or in solid solution in various sulphides. It forms no other natural compounds. The primary ore of silver is apparently the sulphide, argentite; but this is not a very important ore. Most silver is obtained from argentiferous galena or from a large number of complex silver ores containing antimony, arsenic, sulphur, and other elements found in the zone of secondary enrichment; native silver and silver chloride are also important ores. Platinum occurs almost entirely as the native metal in serpentines and in alluvial deposits derived from serpentines. A little platinum is obtained from the residues in the smelting of other metals. Mercury is found as sulphide, cinnabar, either in mineral veins or as a dissemination in sandstones and limestones. The chief primary ore of copper is chalcopyrite or copper pyrites; this when oxidised and reprecipitated as before described forms secondary sulphides, often complex, carbonates, and native copper. Tin is found chiefly as the dioxide, cassiterite, in lodes and veins and to a small extent as stannite, a complex sulphide containing also lead, zinc, and iron. Alluvial tin is very important. Lead and zinc generally occur together, the primary ores being the sulphides galena and zinc-blende; the commonest oxidised ores are anglesite ($PbSO_4$), cerussite ($PbCO_3$), and the carbonate and silicate of zinc. Antimony and arsenic form sulphides and a large number of complicated minerals, in many of which the antimony and arsenic act as acid-forming elements, commonly as sulphantimonides and sulpharsenides. Bismuth occurs native and as sulphide and other compounds. Nickel and cobalt combine with sulphur and arsenic, and also occur as oxidised minerals derived from the sulphides and arsenides. Manganese forms a large number of different oxides, also carbonate; most of these seem to be formed by oxidation of primary silicate. Iron is known in the native state in meteorites, alloyed with nickel, and in one or two terrestrial localities in basalts; but the sole practical sources are various oxides, hydroxides, and carbonates, which may be of igneous, metamorphic, or sedimentary origin. The genesis of the chief types of these deposits has already been described in some detail. There are also certain metals used for special purposes that are exploited in comparatively small quantities, such as chromium, tungsten, molybdenum, and vanadium, used for hardening steel, and the metals of the rare earths, employed for incandescent gas-mantles. Chromium occurs chiefly as chromite in ultrabasic igneous rocks; tungsten and molybdenum chiefly belong to the pneumatolytic phase of granite intrusions; while the metals of the rare earths are found in pegmatites and in sands formed by weathering of granitic rocks.

CHAPTER XVI

THE PRINCIPLES OF STRATIGRAPHY

To a large extent the previous chapters have been devoted to the consideration of the records of past events furnished by a study of the earth's crust. It is the special function of stratigraphy to discover and arrange these records, and, with the aid of other branches of the science, to decipher their meaning.

It was amongst the newer rocks that the science of stratigraphy arose. In the more ancient parts of the earth's crust the stratification is often far from clear, and the rocks are frequently so altered that their origin is obscured. To the unaided eye there is nothing in a slate to suggest that it was once a mud, or in a quartzite to show that it was ever a bed of sand.

It is otherwise with more modern rocks. The stratification is generally distinct, and the beds themselves are often similar to deposits which may now be seen in process of formation. The clays are not unlike the muds of existing rivers, and many of the sandstones are evidently compacted sands.

The Law of Superposition.—As soon as it was realised that the stratified rocks were *deposits*, the foundations of the science were laid. For at once it followed that in all normal cases each bed is older than the one that lies upon it, and newer than the one on which it rests. And this is the fundamental principle of stratigraphy. It is often called the law of superposition.

The law assumes that the beds were laid down one upon another, and it does not hold excepting when the stratification is due to deposition. An intrusive sill may to all appearance be a bed, but it is not older than the bed that lies upon it. The foliation of a gneiss or schist may simulate stratification; but it is not due to deposition; and the law of superposition does not apply.

It is only occasionally that such cases lead to any serious difficulty; and generally, in any single section, such as a quarry or sea-cliff, it is easy to determine the order of succession of the strata, and consequently their relative age. But to do this even in a hundred sections would be of little value unless there were some means of linking together or correlating the sections. If, however, it is possible to show, for example, that bed 6 at the top of section A is the same as bed 1 at the bottom of section B, then we know that the beds in B are the continuation of the series of which a part is shown in A. And if, in a similar way, the correlation of the beds can be continued from section to section, the complete succession throughout a whole district may be determined.

The correlation of the various sections is carried out in several ways. In a region that is destitute of vegetation and bare of soil, the outcrop of some particular bed may be seen to pass from one section to another. In a country such as England, where the rocks are generally concealed, the process is not so easy. Some of the beds, however, will be harder than the rest; and usually a hard bed will protrude at intervals through the soil, or its outcrop will form a ridge that can be traced, although the rock itself is hidden.

Sometimes there may be a bed of such peculiar character that it can be recognised at once. In that case, even if it be not visible in the intervening country, it will serve as a datum line for the comparison of the sections in which it occurs. But however remarkable the bed may be, it is always possible that there may be others of the same kind in the district, and care is therefore necessary in making use of this method.

Apart from the complications introduced by folds and faults, the chief difficulty in the application of the law of superposition arises from the fact that deposits change their character laterally. When a limestone lying between two beds of shale is traced across the country, it often happens that layers of shale appear within it. Gradually the shales thicken and the limestone thins, until at last the whole series becomes a mass of shale. It may be quite impossible to say how much of the shale represents the original bed of limestone.

Nevertheless, the law of superposition will generally enable a geologist to determine the order of succession in any particular district with a fair degree of accuracy. Sometimes, however, it fails; and evidently it does not help him to compare the rocks of one region with those of a distant and disconnected area. But when the direct application of the law becomes impossible, palæontology lends its aid.

Correlation by means of Fossils.—In the early part of the nineteenth century it was shown by William Smith, an English surveyor and engineer, that each bed or group of beds is characterised by a definite set of organic remains. It can be recognised by its fossils at least as readily as by its lithological nature. In fact, the fossils are a safer guide than the lithology, for deposits of very different age may be remarkably alike.

The discovery of this principle led to far-reaching results. It then became possible to correlate the rocks of England with those upon the Continent; and, as time went on, the correlation was extended even into the most distant parts of the globe. Gradually the stratified rocks were arranged in order, and a complete scheme of classification was evolved upon the plan initiated by William Smith.

The full development of the method of correlation by means of fossils was hardly possible until the doctrine of evolution had been formulated. As long as species were looked upon as separate creations, the laws which govern their distribution could scarcely be understood; and indeed they cannot be completely understood until our knowledge of the laws of variation is less imperfect than it is at present. But the first principle of stratigraphical palæontology may be stated thus: Every species, whether of plant or animal, lives only for a limited period upon the earth and then dies out; and once extinct, it never reappears.

A similar statement might be made concerning individuals, and the two statements rest upon the same kind of evidence. The first part scarcely requires any further remark. With regard to the second part, it should be noted that in any limited area a species may disappear and reappear, not only once but many times in succession. If the conditions become unfavourable, it withdraws; and returns with the return of the conditions that favoured it. But all the evidence goes to show that if a species becomes extinct throughout the globe it never reappears.

If we imagine the whole series of stratified deposits arranged in a column in order of age, each species will therefore have a certain vertical range (often called its range in time); and any bed in which it occurs must lie within that range. The vertical range may be great or small; and the smaller it is the more exactly does the occurrence of the species fix the stratigraphical position of the bed in which it is found.

But there are many difficulties in the application of this principle.

It is not possible to define precisely what constitutes a species The term is an artificial one, and is used by some authors in a much more restricted sense than by others. Sometimes it can be shown that one species passes into another by a series of almost imperceptible gradations. Whether this was always the case remains to be proved; but many species had no definite beginning and no definite end, and their vertical ranges accordingly are also ill-defined.

The vertical range of a species is not exactly the same in all parts of the world. A species begins in some particular district, and from there it spreads. At some period in its life it attains its maximum development, and then it dies out gradually or suddenly. It does not necessarily survive latest in the area in which it originated.

This is shown diagrammatically in Fig. 95, which is a 'distribution-diagram' of an imaginary species. The ordinates represent time and the abscissæ space. A, B, C, D, are different localities.[1] The base-line denotes the date at which the species began, and the spaces between the horizontal lines represent equal periods of time. The species originates at C. At the end of the first period it spreads from A to D. It then begins to die out, and after living for three periods, disappears at B.

If our first observations were made at C, the species would be found only in the deposits of the first and second periods. If the species were subsequently discovered at B, it would naturally be assumed at first that it belonged to one of these two periods, whereas it may really belong to the third.

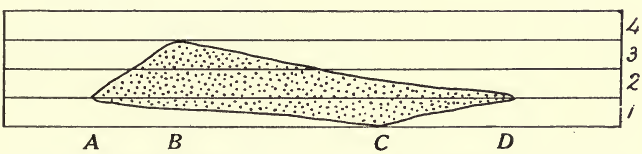


FIG. 95.—DISTRIBUTION-DIAGRAM OF AN IMAGINARY SPECIES.

Accordingly, even if we know exactly the vertical range of a certain species in England, the discovery of the same species in Australia does not prove that the deposits lie within the same range. But the distribution-diagram is not likely to be identical for any two species; and therefore the greater the number of species common to the Australian and the English deposits, the greater the probability that they are of approximately the same age.

It is not possible to construct a distribution-diagram of an actual species with any approach to accuracy. Periods of equal length may be represented by very unequal thicknesses of deposit, and there is no geological measure of time. But the imaginary diagrams in Fig. 96 show the general nature of the differences which undoubtedly exist between different species in respect of their distribution; and a comparison of the diagrams will show why some groups of animals are of much greater value in stratigraphy than others.

In order that a species may be useful for correlation, it should fulfil the following conditions:—

[1] For simplicity these points are supposed to be in the same straight line. An actual distribution-diagram should be in three dimensions.

1. Its total vertical range should be small. In general this implies that it must belong to a group in which evolution is proceeding rapidly. New forms are quickly being produced and quickly replace the species from which they are derived.

2. It must be easily and rapidly distributed, so that the interval between its origin and its maximum extension may be short. On *a priori* grounds, marine forms which are either floating or free-swimming for at least a portion of their lives may be expected to fulfil this condition most completely.

3. Its maximum extension must be considerable. A form which always has a limited geographical distribution can only be of local value.

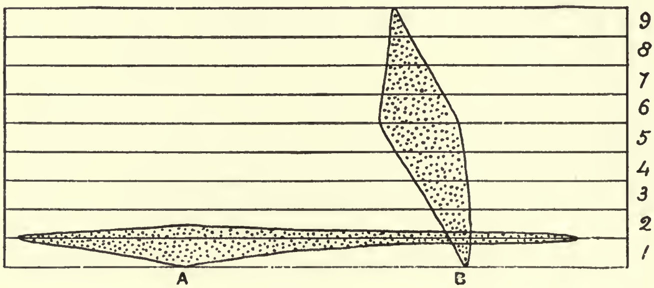


Fig. 96.—Distribution-diagrams of Species.

A, Useful for purposes of correlation; *B*, Of little use.

Of all the groups of animals that have existed on the earth, the most useful, owing to the wide geographical distribution of the species and their small vertical range, have been the trilobites and graptolites in the older Palæozoic rocks and the ammonites in the Mesozoic beds.

But however wide the distribution of a species may be, there was never one, we may well suppose, that overspread the whole earth. Every species has its limitations. Some can live only on the land, others only in the water. Some require fresh water, others salt water. Some dwell in the deep oceans, others on a shelving shore. Some need a sea that is free from sediment, others flourish only where the rivers bring down mud from the neighbouring land.

Consequently the fossils in a bed depend not only on the time when it was formed, but also on the conditions under which it was deposited. A limestone and a clay, even if they belong to the same period, will usually contain faunas which are more or less distinct. When a geological series or system is in one district composed chiefly of limestone and in another of clays and shales, it is usual to speak of these different types of deposit as different 'facies.' Thus we may have a calcareous facies and an argillaceous facies of the Lower Carboniferous. Or the facies may be named after the predominant element in its fauna. In the Ordovician system we may recognise a graptolitic facies, in which the principal fossils are graptolites, and a shelly facies, in which brachiopods and other shells abound.

Fortunately there are forms that can adapt themselves to various conditions, and usually the different facies of a geological series will have some species in common. Moreover, the change from one type of deposit to another is generally more or less gradual, and where the change takes place there will be a certain amount of interstratification of the two facies.

Classification of the Stratified Rocks.—As the order of the stratified rocks was gradually made out, it became necessary, if only for convenience, to divide them into groups. The divisions that were first adopted were based upon lithological characters. There is, for example, in the Midland counties, a group of red sandstones and marls followed by a series of dark clays with occasional bands of limestone. These were recognised as two distinct divisions. The former was named the New Red Sandstone and the latter the Lias. But as the study of the science proceeded, it became evident that lithological divisions are unsatisfactory, and more and more importance was attached to fossils.

Often the passage from one set of beds to the next is very gradual, and the fauna also alters gradually; but sometimes there is a rapid change of character either in the deposits or in the fossils, or in both; and occasionally there is an actual break or interruption of continuity, and the beds and fossils above are quite distinct from those below. Some of the breaks are purely local, but others extend over a very wide area. Most of them are marked by unconformities; but sometimes the unconformity is very slight, and occasionally there is no unconformity at all.

The more widespread and important breaks are taken as dividing lines; and dividing lines are also drawn where the fauna and lithology change rapidly, even though there may not be any real interruption of continuity. In this way the rocks of the earth's crust have been divided into four great divisions, which are often known as groups. The groups are subdivided into systems, the systems into series, and the series into stages.

According to the scheme which is usually adopted, the groups and systems are as follows (in descending order):—

Groups	Systems
Kainozoic or Tertiary	Neogene. Palæogene.
Mesozoic or Secondary	Cretaceous. Jurassic. Triassic.
Palæozoic or Primary	Permian. Carboniferous. Devonian or Old Red Sandstone. Silurian. Ordovician. Cambrian.
Pre-Cambrian or Archæan.	

Notes on the Scheme of Classification.—The Kainozoic Group is often divided into five divisions, viz. in descending order, Pleistocene, Pliocene, Miocene, Oligocene, Eocene. These are sometimes called Systems, but are more commonly looked upon as Series.

The Ordovician and Silurian are often grouped together as a single System, which is called the Silurian System. The Ordovician then becomes the Lower Silurian, and the Silurian of the above table is called the Upper Silurian.

The term Archæan is sometimes restricted to a portion of the pre-Cambrian Group.

The systems are far from equal in thickness. Their development varies from place to place; but in Great Britain generally most of the Palæozoic systems are considerably thicker than those of the Mesozoic and Kainozoic groups.

Because, in the scheme of classification, the strata are arranged in order of deposition, the names which are applied to the subdivisions may also be applied to the periods of their formation. Thus we speak not only of Palæozoic rocks or beds, but also of Palæozoic times. The term Cambrian signifies not only the deposits belonging to the system, but also the period during which the system was deposited. Conventionally the period of time during which a group was formed is called an era; a system corresponds with a period; a series with an epoch; and a stage with an age. But few geologists adhere rigidly to this convention.

Two other terms in common use require a few words of explanation.

A zone is a layer of deposit, of limited but variable thickness, characterised by a very definite assemblage of species, which distinguishes it from all other deposits. Usually one or more species are either confined to the zone or are abundant in the zone and rare outside its limits. The zone is named after one of these characteristic species.

Thus we speak of the *Rastrites maximus* zone, the *Ammonites margaritatus* zone, &c. When a zone is clearly defined, we may safely assume that wherever it is found the deposits which form the zone were approximately contemporaneous.

The term **horizon** is used to denote a definite position in the scheme of classification. Theoretically it represents an actual date, just as a system represents a period of time. When we say that a certain bed in England is on the same horizon as a certain bed in America, we mean that they were formed at the same time. In theory the boundaries between the various systems are definite horizons. In England it is customary to include in the Cambrian system certain deposits which on the Continent are usually placed at the bottom of the Ordovician system. This is expressed by saying that we draw the boundary at a somewhat higher horizon than the Continental geologists.

Since the principle of correlation by means of fossils was discovered in England, it was in England that the first outlines of the modern scheme of classification were sketched, and the boundaries between the systems were drawn at the horizons that seemed most natural in Northern Europe. But as the study of stratigraphy was extended into distant lands it was found that a system which in Europe is sharply limited, in another region may be vague and ill-defined. Changes in the fauna and in the nature of the deposits are caused by changes in conditions, and these changes are not contemporaneous throughout the globe. A break is a natural line of division wherever it is found; but breaks do not everywhere occur at the same horizons.

A break indicates that an interval of time is unrepresented by deposit. It may be simply that no sediment was laid down where the break occurs. This may happen, for example, if the rivers or currents that brought the sediment were temporarily deflected; but such a break is not likely to be widespread or of long duration. More often a break is due in part to the removal of material that has already been deposited. Generally it means that for a time the area was land, but sometimes the denudation was accomplished on the floor of the sea by an increase in the strength of the currents. In any case the material that is removed must be deposited elsewhere, and consequently a break in one area implies deposition in some other region, and a universal break is almost an impossibility. In England there is a strongly marked break between the Carboniferous and the Permian; in the East there is a perfect passage from the one system to the other. And many other similar examples might be given.

A rapid change in deposits or fauna, without any actual break, may be brought about in several ways; but always it implies an equally rapid change of conditions. An arm of the sea may be cut off and converted into a lake, and in a short time the lake will usually become, according to circumstances, either salter or fresher than the open ocean. In either case the change of conditions will be reflected in the deposits and the fauna. A change of the opposite kind is likely to be still more sudden. When the sea breaks into a fresh-water lagoon, most of the original denizens will quickly die and their place will be taken by invaders from the sea. In such ways as these may be produced the sudden transitions which sometimes occur from one type of sediment to another, without any interruption of continuity. But evidently such changes cannot be universal.

Since neither breaks nor rapid changes are universal, it is evident that the limits of the systems are necessarily arbitrary. If natural in one region they must be unnatural in another; and accordingly we find that there are difficulties in applying the European classification in India and South Africa.

Geological History.—As the object of stratigraphy is to decipher the history of the earth, it is not sufficient to determine the succession of the rocks and to arrange the fossils in order of antiquity. This is the first step only. The next is to deduce the conditions that prevailed during different periods. The method of procedure is to compare the rocks with the deposits of the present day, and the fossils with the animals and plants that now inhabit the globe.

The characters of the deposits formed under different conditions have been described in previous chapters, and no further reference is needed here. The study of the fossils is properly the province of Palæontology, but a few general observations on the evidence which they afford may be useful.

Terrestrial forms are often easily distinguished. The teeth of land mammalia, the wings of insects, the fronds of ferns and the leaves of trees can generally be recognised as such even by the untrained eye. But other remains are not always so characteristic, and it may require a specialist to determine whether they belong to terrestrial or aquatic forms. It is worthy of notice that the only land Mollusca are gastropods, and the shells, when they possess shells, are always holostomatous, and generally rather thin.

When terrestrial forms occur alone, the bed in which they are found was deposited, presumably, upon the surface of the land itself; but when they are associated with aquatic forms their presence only proves that land was near.

Terrestrial deposits are rare, and usually the question that arises first with regard to any bed is whether it was fresh-water or marine. Radiolarians, corals, echinoderms, brachiopods, pteropods and cephalopods are now found only in the sea, and the presence of any of these may be taken as a sure indication that the deposit was marine. Foraminifera and sponges are almost equally conclusive. Graptolites and trilobites are now extinct, but their associations with other forms show that they were marine. Lamellibranchs and gastropods occur both in the sea and in fresh water; but the number of fresh-water forms is comparatively small, and the fresh-water gastropods are generally distinguished by possessing a thin and fragile shell.

When it has been shown that a deposit was marine, it is desirable to determine whether it was laid down in deep or shallow water; and this is often a matter of considerable difficulty. At present many genera live only at certain depths, but it is doubtful if their ranges were equally limited in the past. The evidence afforded by groups of animals rather than by genera is sometimes of more value, but even this is often doubtful.

In many cases deposits consisting largely of foraminifera or radiolaria have been taken as indicative of deep waters. But they are evidence of clearness rather than of depth: where sediment is abundant such very minute shells are lost in the thickness of deposit. A somewhat similar observation applies to all floating forms that are not affected by the depth of the water beneath them: their remains will be relatively most abundant where the sediment is least. Graptolites have been supposed to point to a considerable depth, but whether they were floating forms or not, they follow the same rule. They are most abundant where deposition was slow, but they occur occasionally in sandstones and other rapidly formed deposits.

Reef-building corals, in the past as in the present, appear to have been confined to shallow water. Of the Mollusca it may be said generally that the shallow-water forms possess thick shells, and those that live at great depths, as well as those that float upon the surface, have thin ones; but to this rule there are exceptions.

From the fossils that are found in a deposit it is sometimes possible to infer the climate that prevailed when it was formed. In the London Clay, for example, leaves of palms and other tropical plants occur, together with turtles, crocodiles and other animals which now live only in warmer latitudes. Hence we may reasonably conclude that when the London Clay was deposited, the temperature of the area was considerably higher than it is at present. At the close of the Pliocene epoch, on the other hand, the dwarf willow and dwarf birch grew in England, which shows that the climate was arctic in its severity.

Plants are in general more useful in this respect than animals, because their distribution is usually more strictly limited by climatic conditions. But whether plants or animals are our guides, the conclusions that may be drawn from them are most trustworthy in the case of the more recent beds, for in these the fossils are most closely allied to the forms that now inhabit the earth. In the older rocks the types become so different that their evidence is less decisive. In modern seas reef-building corals require a mean temperature not less than 68° Fahr. It is probable, therefore, that coral-reefs in ancient rocks also indicate a warm sea; but the inference is open to doubt, for the older corals differ in structure from the modern forms, and they may have differed in habit.

Astronomical considerations suggest that even in the Palæozoic era the climate cannot have been uniform throughout the globe; and several attempts have been made to show that the northern faunas differed from the southern. In the Ordovician and Silurian systems, for example, there are many trilobites which occur both in England and in Scandinavia, but which are unknown in Bohemia; and there are many Bohemian forms which are not found in the north of Europe. But there are other causes besides climate which influence distribution, and it is difficult to disentangle their effects. A barrier between two seas will prevent the faunas from mixing, or the differences may be due to differences in depth or other conditions.

It was at one time thought that in the deposits of the Jurassic system there were clear indications of climatic zones. Three contemporaneous faunas were recognised in Europe, each distinguished by certain types of ammonites and other fossils; and these three faunas were traced around the world in belts, roughly parallel to the equator. It was believed that they represented respectively a boreal zone, a temperate zone, and a tropical zone. But recent observations have shown that the zonal arrangement is far from perfect. Where the deposits at the equator are similar to those of Central Europe, the fossils also are similar. The distribution of the faunas was, in fact, determined not by climate but by facies.

The absence or rarity of fossils indicates either that the conditions were unfavourable to life or that they did not lend themselves to the preservation of organic remains. By itself it does not lead to any certain conclusions; but when the rarity of fossils is associated with the presence of deposits of salt, wind-blown sands, &c., as in the Trias, we may infer that desert conditions prevailed. When the unfossiliferous beds contain glaciated boulders, an arctic climate is suggested.

Maps and Literature.—In the study of stratigraphy it is important that the student should obtain a clear idea of the distribution of each system. The maps which are given in the text are intended to assist him; but he should also make constant use of the geological map of the British Isles published by the Geological Survey (price 2*s*.). For further details he may refer to the Geological Survey Index Map of England and Wales on the scale of four miles to the inch, now published in twenty-five sheets. He will find it helpful to procure the particular sheet in which his own district is situated. The one-inch map of the Geological Survey gives still fuller information.

Owing to the amount of local and palæontological detail which they contain, very few stratigraphical papers are suitable for the student's reading. Until he has fairly mastered the following pages he may be recommended to confine his outside reading to work that deals with his own district. For this purpose the volume called 'Geology in the Field,' issued by the Geologists' Association, will be found very useful. It is published in four parts (price 5*s*. each) by Edward Stanford. References to important papers will be found in that volume; and further references may be obtained from the larger works on stratigraphy, especially—

H. B. Woodward, *The Geology of England and Wales.* George Philip and Son. 2nd ed. 1887.

A. J. Jukes-Browne, *The Student's Handbook of Stratigraphical Geology.* Edward Stanford. 2nd ed. 1912.

Sir Archibald Geikie, *Text-book of Geology.* 2 vols. Macmillan and Co. 4th ed. 1903.

The first of these is still useful for the very full references which it gives to the literature of the subject, but in many respects it is necessarily out of date.

CHAPTER XVII

THE PRE-CAMBRIAN OR ARCHÆAN ROCKS

THE oldest beds in which recognisable fossils have been discovered form what is known as the Cambrian system; but beneath them lies a still more ancient set of rocks in which no certain sign of life has yet been found. These have sometimes been called the Azoic system, but since they may ultimately be shown to contain fossils, they are better named pre-Cambrian or Archæan. At various times and in various countries remains of organisms have been reported to occur in them, but in no case does the evidence seem conclusive.

Everywhere in the British Isles there is a marked unconformity between the pre-Cambrian and the later deposits. Sometimes it is the Cambrian beds which rest upon them, sometimes more recent strata. In the latter case the pre-Cambrian age of the rocks is inferred mainly from their lithological character, a guide which in the past has often proved delusive. Even when the Cambrian beds are present, it is not always easy to demonstrate the unconformity at their base; and on this account it is sometimes difficult to determine whether the rocks in question belong to the pre-Cambrian or to the base of the Cambrian system.

In the British Isles the largest area of pre-Cambrian rocks (Fig. 97) lies towards the north-west, forming the western coast of Sutherland and Ross, and almost the whole of the Outer Hebrides. Smaller tracts occur in Anglesey, North Wales and South Wales; and isolated masses rise through the newer beds of the Midlands and the Welsh borders. Possibly the rocks of Start Point and the Lizard, in the south of England, may be pre-Cambrian, and it is probable also that some of the rocks of Connemara and other parts of Ireland may belong to the same period; but as no undoubted Cambrian beds are known in these districts, the age of the rocks in question is uncertain.

The pre-Cambrian system includes rocks of three distinct types, which may be briefly described as gneissic or schistose, volcanic and sedimentary. The gneissic type is believed to consist chiefly of metamorphosed plutonic masses. The volcanic type is formed of tuffs and

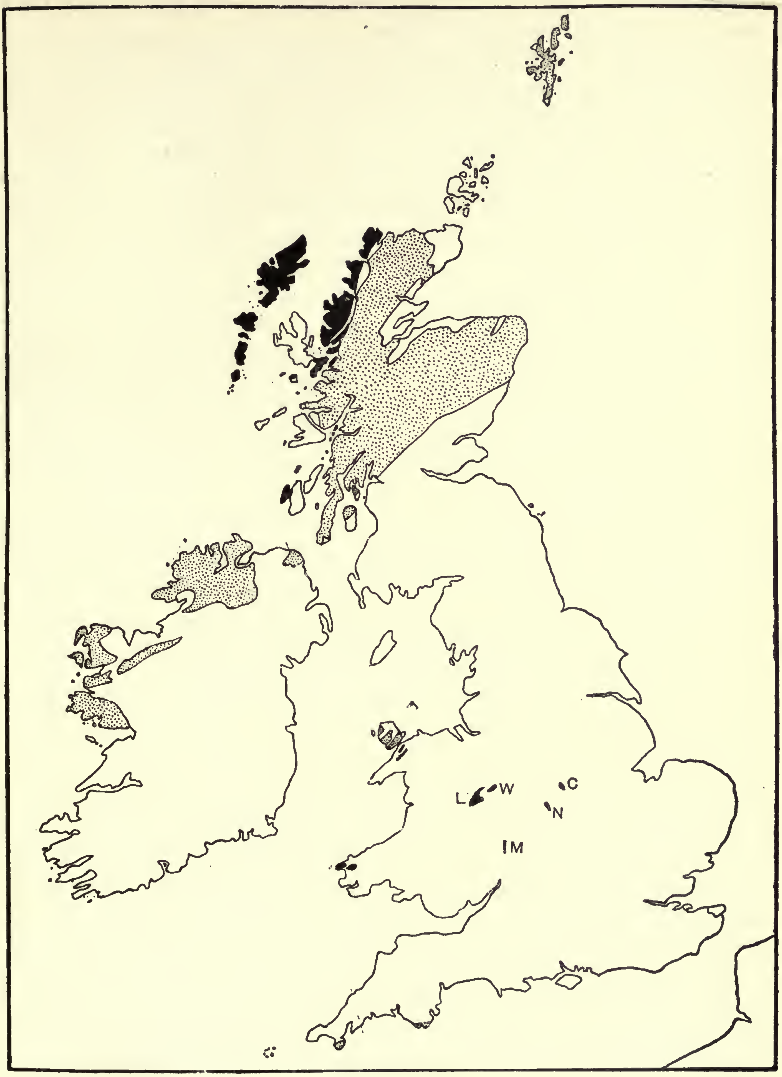


Fig. 97.—Map of the pre-Cambrian Rocks.

Undoubted pre-Cambrian outcrops—black ; doubtful outcrops, and areas which consist of pre-Cambrian and later rocks folded together—shaded.

W, The Wrekin ; *L*, The Longmynd ; *M*, The Malvern Hills ; *N*, Nuneaton ; *C*, Charnwood Forest.

lava-flows, which are usually much less altered. The sedimentary type consists of arkoses, grits and slates.

It is uncertain how far these types represent distinct periods; but there can be little doubt that in general the gneissic rocks are the oldest. They have suffered by far the highest degree of metamorphism, and in Scotland they are overlaid unconformably by arkoses and grits of the sedimentary type. The relative age of the volcanic rocks has not been determined with the same certainty. They generally occur in separate areas; and it is possible that the sedimentary deposits were laid down in one region while at the same time the volcanic rocks were erupted in another. In Scotland, however, pebbles of rhyolitic lava are commonly found in the sedimentary series, and hence it may be inferred that there must have been an earlier volcanic series from which the pebbles were derived. In Shropshire both the sedimentary and volcanic series are present, but separated by a fault, so that their relations to each other are obscure. The sedimentary series, however, contains fragments of lava which appear to have been derived from the volcanic series.

Provisionally, therefore, it may be assumed that the three types represent three more or less distinct periods, and the pre-Cambrian rocks may then be subdivided into three series as follows (in descending order) :—

3. Torridonian—Sedimentary.
2. Pebidian or Uriconian—Volcanic.
1. Lewisian or Hebridean—Gneissic.

Scotland

Archæan rocks occupy a broad strip of country upon the western coast of Sutherland and Ross, extending from Cape Wrath on the north to Loch Alsh on the south; and the massif of which this is the eastern border stretches westward to the Outer Hebrides. Two divisions are clearly recognised. The Lewisian gneiss forms almost the whole of the Outer Hebrides, but upon the mainland it is frequently covered unconformably by the sedimentary deposits of the Torridonian. No volcanic series is met with; but, as has been noted above, pebbles of lava are often found in the Torridonian. In many places basal Cambrian beds are seen to rest unconformably on both the Torridonian and the Lewisian, and thus the pre-Cambrian age of these rocks is indisputably established.

The **Lewisian** gneiss may be divided into (1) a 'Fundamental Complex,' and (2) a series of igneous rocks intruded into the complex in the form of dykes and sills.

The Fundamental Complex is a mass of gneisses and schists of various composition and of varied structure. Owing to subsequent earth-movements and metamorphism it is not possible to separate the individual members. Even the later dykes and sills have sometimes been converted into schists and incorporated indistinguishably into the complex. But on the whole the schists appear to be metamorphosed sediments, and the gneisses metamorphosed plutonic masses. The former are relatively of small importance, and are found chiefly in the valley of Loch Maree. The latter form by far the greater part of the complex. They vary in composition from ultrabasic to acid, the basic portions being earlier than the acid. Usually they are banded or foliated, but not uncommonly the structure is on so large a scale that it is not visible in hand-specimens, and sometimes it entirely disappears and the rocks become indistinguishable from an ordinary plutonic mass. The banding and foliation appear to be due chiefly to three causes : (1) differentiation of the ferro-magnesian and quartzo-felspathic constituents while the rock was still molten and flowing; (2) intrusion of the residual molten matter into the parts which had already solidified; (3) earth-movements after consolidation.

Of the dykes and sills which have been intruded into the Fundamental Complex, a small proportion are post-Torridonian in age and need not be considered here. But by far the greater number were intruded before the Torridon sandstone was laid down. Like the gneiss itself, they vary in composition from ultrabasic to acid. The ultrabasic dykes usually trend from east to west, and are comparatively of small importance. The basic dykes, which are mostly dolerites, occur in extraordinary numbers, especially between Loch Laxford and Enard Bay, and generally run from W.N.W. to E.S.E. The acid intrusions, which form both sills and dykes, are also very abundant, and consist for the most part of granite and pegmatite. The basic dykes appear to be the oldest of the series.

These intrusions evidently took place after the Fundamental Complex as a whole had solidified, and they were subsequent to the primary banding of the mass; for in many places, while themselves unfoliated, they traverse banded gneiss. At a later date, but still before the Torridon sandstones were deposited, earth-movements took place, accompanied by shearing along planes running from E. to W. or E.S.E. to W.N.W.; and along these planes the dykes are themselves converted into schists.

The **Torridonian** series is a stratified deposit, which throughout the greater part of its extent rests horizontally or with a gentle dip upon the Lewisian rocks (Fig. 98). No sign of the great disturbances which affect the latter is to be found in the former, and the Lewisian gneiss must have attained its present features before the sedimentary series was deposited. If the Fundamental Complex was originally

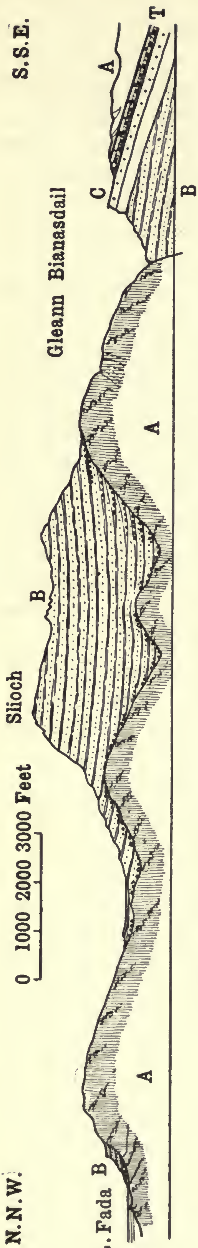


FIG. 98.—SECTION FROM LOCH FADA ACROSS SLIOCH TO GLEANN BIANASDAIL.

(From *Memoirs of the Geological Survey*, 'The Geological Structure of the North-west Highlands.' Reproduced by permission of the Controller of H.M. Stationery Office.)

A, Lewisian gneiss; *B*, Torridon sandstone; *C*, Cambrian; *T*, Thrust-plane.

a deep-seated plutonic mass, the whole of the overlying rocks must have been removed before the Torridonian series was laid down, and the interval of time represented by the unconformity between the two must be enormous.

The greater part of the Torridonian series consists of red felspathic grits and sandstones (arkose), generally coarse in texture, but with occasional thin beds of fine-grained micaceous shale and sandstone. Where they rest upon the older rocks an angular breccia is often found, and bands of conglomerate occur at different horizons. The whole series is characterised by false-bedding, and appears to have accumulated quickly. A remarkable feature is the freshness of the felspar grains, which has led to the suggestion that disintegration must have been more rapid than is usual in a temperate climate.

Although red is the predominant colour of the formation and the texture is generally coarse, neither colour nor texture persists throughout the series. Especially towards the top and bottom shales occur in some localities, together with occasional calcareous bands. But these shales were not laid down in deeper water, for, in the lower division at least, their surfaces are marked with rain-pittings and sun-cracks. In the upper shales black phosphatic lenticles have been found, probably indicating the presence of organisms; but the nature of the organisms is not clear, and no other sign of life has been discovered.

The actual basement is usually a coarse conglomerate formed of fragments of the Lewisian gneiss from the immediate neighbourhood. In general, however, the material of which the greater part of the series is composed is not derived from any rocks which now exist on the mainland.

The surface on which the Torridonian series rests is very irregular. It has the form of an undulating plateau carved into mountains and valleys; and the Torridonian deposits fill the valleys and spread over the hills. The height of some of the hills was certainly not less than 2,000 feet, and probably many of them were considerably higher. In some cases, by the removal of the sandstones, the actual Torridonian landscape is exposed to view and the present rivers follow the course of the old valleys.

Much of the material of which the Torridonian series consists is well-rounded, and must have been laid down by water. The false-bedding shows that the currents which bore it were variable in direction and strength, and the size of the pebbles indicates that at times their force was great. But since the deposits fill the valleys, it is evident that in the lower ground the currents ceased or their velocity was diminished, and they were unable any longer to carry the material which they had brought. The deposit, in short, is of torrential origin. It was washed down by mountain streams and laid upon the valley floors, where the waters spread and lost their force. It has already been remarked that the freshness of the felspars indicates a rapidity of disintegration greater than is usual in temperate climates, and it has been suggested that this was due to the action of frost.

So vast an accumulation of horizontally bedded deposits, burying hill and valley indiscriminately, finds no parallel at the present day except in the drier regions of the globe, such as the 'dasht' of Baluchistan and Afghanistan. In these there is the same rapidity of disintegration of the solid rock and accumulation of loose material. At certain seasons heavy floods sweep the loose debris down the mountain-sides and spread it far and wide over the plains and valleys; but the intermittent nature of the rainfall prevents the establishment of permanent river-courses carrying the material to the sea.

Besides forming the north-western border of Scotland, both the Lewisian and Torridonian rocks take part in the formation of the great series of gneisses and schists which constitute the main mass of the Scottish Highlands.

This mass has been pushed forward over the rocks of the north-western coast upon a great thrust-plane, or rather a series of thrust-planes, which run from Loch Eireboll to Loch Carron. On the eastern side of the thrust, the folding has been so intense and the structure is so complex that in general it is not possible as yet to separate the pre-Cambrian from the later rocks.

South Wales

In the neighbourhood of St. David's is an elliptical area of igneous rocks. In the earlier issues of the maps and sections of the Geological Survey, Sir Andrew Ramsay appears to have supposed it to consist in part of felspathic ashes, in part of a plutonic mass of granite. In the later issues the ashes were looked upon as altered Cambrian rocks, metamorphosed by the granite.

It was Dr. H. Hicks who first maintained that the whole mass is unconformably overlaid by the Cambrian beds and must therefore be of pre-Cambrian age. Moreover, he divided it into three distinct series, each of which rests, according to him, unconformably upon the one below it. The lowest series, which he called Dimetian, is composed of granitoid gneiss. The second, to which he gave the name Arvonian, is formed of rhyolitic lavas alternating with felsitic breccia and hälleflinta. The third, or Pebidian series, which occupies the greater part of the area, consists mainly of volcanic tuffs with contemporaneous basic lava-flows.

Sir Archibald Geikie after a re-examination of the district, concluded that the tuffs pass upwards conformably into the fossiliferous Cambrian beds and must therefore be considered as the base of the Cambrian system. The Dimetian, he said, is a granite intruded into the tuffs; and the Arvonian is nothing more than a series of veins and apophyses given off from the granite. On this view the whole mass is of Cambrian age, or perhaps the granite and its apophyses may be of even later date.

Another interpretation was brought forward by Prof. J. F. Blake. He agreed with Dr. Hicks that there was an unconformity between the Cambrian and the Pebidian, and with Sir Archibald Geikie that the Dimetian was a true granite and not a gneiss. The mass is therefore pre-Cambrian, but not separable into the series recognised by Hicks. He looked upon the whole as a great pre-Cambrian volcano, and appears to have considered the granite as the neck or core and the tuff as the remains of the old cone.

A more detailed examination of the district has recently been made by Mr. J. F. N. Green. Recognising and mapping various subdivisions in the Pebidian tuffs, he has been able to show that the Cambrian beds rest upon different horizons and must therefore be unconformable. The granitoid rock is intrusive into the Pebidian, but is overlaid unconformably by the Cambrian. His interpretation therefore agrees in many respects with that of Blake.

The Pebidian consists essentially of submarine rhyolitic and trachytic tuffs. The lower part of the series is distinctly more basic, and on the whole coarser than the upper half, and includes some augite andesites. Green recognises fourteen or fifteen constant subdivisions, which arrange themselves naturally into four groups.

The granitoid rock which Hicks called Dimetian consists chiefly of quartz and felspar, with chlorite, and is coarsely granophyric in structure. It varies in texture, and is finer-grained towards its margins. Its boundaries are usually faulted, but it appears to be intrusive, and there is some evidence that the intrusion was laccolitic, lying in large part between the first and second of Mr. Green's groups.

There are many dykes of quartz-porphyry, the Arvonian of Hicks. These are believed by Geikie to be apophyses of the granite; but according to Green they are quite distinct, though perhaps only a later phase of the same rock-magma.

Basic intrusions are also present. Some of these are vesicular, and were described by Hicks as contemporaneous lavas amidst the Pebidian tuffs. But according to Green they are probably all intrusions and of post-Cambrian age.

North Wales

In the north-west of Caernarvonshire two narrow strips of igneous rock rise to the surface from beneath the Cambrian strata. The one extends from Bangor south-westwards to Caernarvon, the other lies parallel some three miles to the south. Both these igneous masses resemble that of St. David's. They consist chiefly of volcanic ashes, agglomerates and quartz-felsites, with a granitoid mass at Caernarvon. There can be little doubt that they are of the same age as the St. David's rocks. It is also nearly certain that the schists and jaspers which form the coast of the Lleyn peninsula from Nevin to Bardsey Island are of pre-Cambrian age.

Anglesey

About one-half of Anglesey is formed of schists and gneiss; but the rarity of fossils and the total absence of any forms characteristic of the Lower Cambrian render it difficult to determine their age with certainty. Some part is admitted on all hands to be pre-Cambrian. Sir Archibald Geikie has himself remarked upon the resemblance of the gneissic core of Central Anglesey to the Lewisian gneiss of Scotland; but he believes the schists of Holyhead and North-west Anglesey to be metamorphosed Ordovician beds. In the present state of our knowledge the age of many of the Anglesey rocks remains uncertain.

Shropshire

A ridge of ancient rock stretches from Wellington towards the south-west, forming the Wrekin, Caer Caradoc and several other smaller hills. The core of the ridge consists in part of rhyolitic lava-flows, in part of volcanic breccias and tuffs; and these are unconformably overlaid by a quartzite containing *Olenellus* and other Lower Cambrian fossils. The volcanic rocks must therefore be of pre-Cambrian age. They were named by Dr. Callaway the Uriconian series, and probably belong to the same series as the Pebidian of St. David's. Similar rocks occur at Pontesford Hill and one or two other points lying on a parallel line some six or eight miles farther west.

Immediately to the west of Caer Caradoc, but separated from it by a fault, is the moorland district of the Longmynd, formed of a vast thickness of slates and grits, the age of which is still uncertain. They were at one time supposed to be the base of the Cambrian system, but they are quite unlike the known Cambrian deposits of the neighbourhood. They are certainly not of later date, and the probability therefore is that they are pre-Cambrian. Their relations to the surrounding rocks are, however, not yet determined.

In general these Longmynd rocks strike about north-east to south-west, and dip constantly to the north-west. Two divisions may be recognised: (1) an eastern, and, presumably, lower series, consisting of grey and green shales and flagstones; and (2) a western series, formed mainly of red sandstones and conglomerates, not unlike the Torridonian sandstones of Scotland.

A few fragments which were supposed to be organic have been found in them, and markings which appear to be worm-tracks and worm-casts are not uncommon in some of the beds. But no unmistakable fossils have been discovered. Rain-pittings and ripple-marks indicate that the deposit was formed in shallow water.

The Malvern Hills

The core of the Malvern Hills is formed of crystalline gneissic rocks, which are probably metamorphosed plutonic masses comparable with the Lewisian gneiss of Scotland. Upon the eastern side are a few patches of volcanic rock such as rhyolites, andesites, basalts and tuffs. These are no doubt the equivalents of the Uriconian series of the Wrekin. Their relations to the gneissic series have not been determined. The junction with the later rocks appears to be always faulted; but pebbles of gneiss and volcanic rock occur in the basal conglomerates of the Cambrian system.

Warwickshire

Small outcrops of volcanic tuff and breccia occur near Birmingham and Nuneaton, where they are overlaid by Lower Cambrian beds. The exposures are too obscure to demonstrate any unconformity, but the base of the undoubted Cambrian contains fragments derived from the volcanic tuffs below. The latter are presumably of pre-Cambrian age and belong to the Pebidian or Uriconian series.

Leicestershire

A much larger area of ashes, tuffs and agglomerates, interstratified with slates and grits, forms the upland district known as Charnwood Forest. Here the volcanic rocks rise through Triassic beds, which rest unconformably upon them. No Cambrian strata are known in the vicinity; and there is therefore no palæontological evidence of the age of the Charnwood rocks. But they are quite unlike any known Palæozoic series in Great Britain, and they are believed to be pre-Cambrian. Several large masses of granophyre and other rocks have been intruded into the series, certainly before the Trias was deposited.

CHAPTER XVIII

THE CAMBRIAN SYSTEM

The Cambrian beds of Great Britain (Fig. 99) occur generally in the same areas as the pre-Cambrian rocks already described; but they are absent in Charnwood Forest, and, on the other hand, they are found in the Lake District, where pre-Cambrian rocks perhaps exist but have not yet been proved.

The principal outcrops are situated in (1) North Wales, (2) South Wales, (3) Shropshire, (4) the Malvern Hills, (5) Warwickshire, (6) the Lake District, (7) the North-west Highlands. Some of the rocks of Wicklow and Wexford are supposed to belong to this system, but no undoubted Cambrian fossils have been found anywhere in Ireland.

In the British Isles the formation consists chiefly of sandstones and shales, often converted into quartzites and slates. Grits and conglomerates occur towards the base, but except in the north-west of Scotland limestones are rare. Some of the lower beds appear to contain a certain amount of volcanic material, and occasional volcanic bands occur at a higher horizon; but on the whole, in our islands, the period was remarkably free from manifestations of volcanic activity.

The deposits appear to be entirely marine. In Wales the coarser beds, which no doubt indicate a shallower sea, are found especially towards the base of the system (Harlech grits) and again towards the middle (Lingula flags). There were therefore, in all probability, two shallow-water phases, separated and followed by periods of deeper water, during which the more shaly beds were laid down. Upon the Welsh borders the second of the shallow-water phases is represented by a gap in the succession.

In Scotland the system begins with arenaceous deposits and becomes more and more calcareous towards the top, indicating, apparently, a continuously deepening sea.

Owing to folding and faulting, most of the estimates of thickness of the Cambrian deposits are unreliable. In order, however, to give some idea of the quantities involved, it may be said that in Wales, where the system is most massively developed, the total thickness has been put at 12,000 feet. But this is probably an over-estimate.

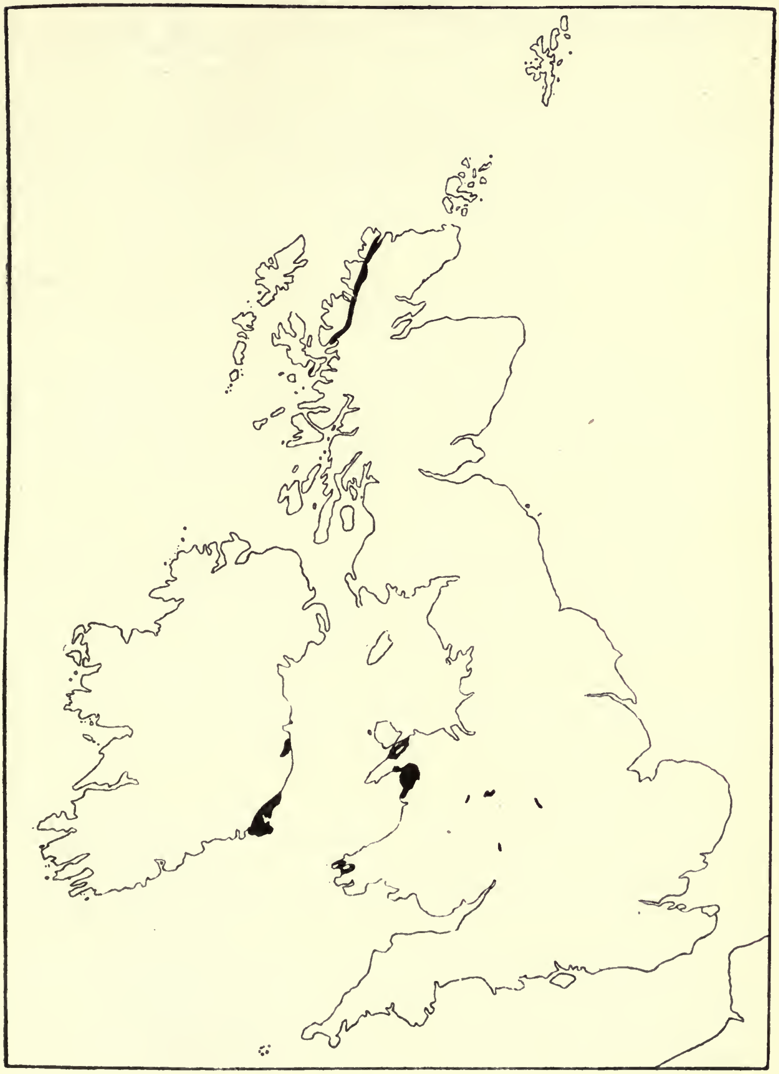


FIG. 99.—THE CAMBRIAN SYSTEM.

The subdivision and classification of the system was originally based upon the lithological differences due to changes in the depth of the sea. But although the changes were widespread, they were by no means universal, and for comparison with the rocks of other countries it is necessary to adopt a palæontological classification according to the included fossils.

Fauna.—The most remarkable feature of the Cambrian fauna is its complexity. Although it is the earliest known to science, it is by no means primitive in constitution. It includes a number of highly specialised forms, the evolution of which from any primordial germ of life must have required many ages to complete. Moreover, it contains representatives of all the *phyla,* or main branches, of the animal kingdom excepting only the Vertebrata. Even at this early date the broad lines upon which evolution was to proceed were already settled.

It is apparent, therefore, that the Cambrian fauna can scarcely represent the advent of life upon the globe; but of any earlier appearance there is as yet no certain evidence.

Both in abundance and in stratigraphical importance the brachiopods and trilobites stand in the first rank. The brachiopods are mostly inarticulate, *Lingulella* and *Obolella* being the commonest genera in Great Britain; but the articulate form, *Kutorgina,* occurs in the lowest division of the formation; and *Orthis* is abundant in some of the higher beds.

Of the trilobites, *Olenellus, Paradoxides, Olenus, Conocoryphe, Ptychoparia, Microdiscus* and many others are entirely confined to the Cambrian. *Agnostus* also is especially abundant, but ranges upwards into the Ordovician. Towards the top, in the Tremadoc rocks, several types characteristic of the succeeding system begin to appear, such as *Ogygia* and *Asaphus* (the latter represented by the primitive form *Asaphellus*). But the trilobites were not the only crustaceans that existed. The Phyllopoda, the Ostracoda and the Phyllocarida were also represented.

In the Tremadoc beds are found the earliest forerunners of the important group of graptolites. All of them are branching forms, the most important genera being *Dictyonema* and *Bryograptus.*

But this does not complete the list of the Cambrian fauna. Although their remains are comparatively rare, several other important groups of animals are known to have existed.

Thus the sponges were represented by the Hexactinellid *Protospongia.* Several classes of echinoderms could even then be distinguished. The earliest-known starfishes and crinoids are found in the Tremadoc beds, while cystideans occur in the Middle Cambrian.

The Mollusca are not common, but there were representatives of the three great groups, Lamellibranchia, Gastropoda and Cephalopoda.

Classification of the Cambrian System.—The palæontological classification of the system is based upon the vertical distribution of the trilobites, and four main groups have been distinguished:—

Shumardia Series (with Cambrian and Ordovician genera).
Olenus Series.
Paradoxides Series.
Olenellus Series.

These groups have been recognised over a large part of the globe, and therefore have a higher value than any lithological divisions. Each of the four series can be subdivided into zones characterised by individual species, and many even of these smaller subdivisions can be traced over very wide areas.

North Wales

It was in North Wales that the Cambrian system was first distinguished, and it is here that the upper part of the formation is best known; but unfortunately the lower beds are in general unfossiliferous.

In Western Merionethshire the Cambrian beds rise to the surface in the shape of a dome, known as the Harlech anticlinal, which is continued westward beneath the sea. The gritty beds near the base of the system form the centre of the dome, while the later beds wrap round them in a series of concentric rings broken open on the west. On the northern side of the dome the Cambrian beds sink beneath the Ordovician rocks of Snowdonia, to appear once more against the Archæan masses of North-west Caernarvonshire, where they form a broad band parallel to the Menai Straits.

It is in the Harlech anticlinal (Fig. 100) that the succession has been most completely made out, and there the beds may be grouped as follows:—

4. Tremadoc Series . .	Slates. *Dictyonema, Shumardia, Asaphellus, Angelina.*
3. Lingula Flags . . .	Flags and slates. *Olenus, Lingulella Davisi.*
2. Menevian Series . .	Slates. *Paradoxides.*
1. Harlech Series . . .	Grits, slates below. No fossils.

The **Harlech Series** is finely exposed in the rugged hills which lie to the east of Harlech, where it is formed of coarse greenish-grey grits with bands of green and purple slate. Though no fossils have been found in this series in the Harlech anticline itself, the corresponding beds at the south-eastern corner of the Lleyn peninsula have yielded *Paradoxides Hicksi* and many other species of trilobites characteristic of the Paradoxides series.

The **Menevian Series** consists chiefly of dark slates distinguished

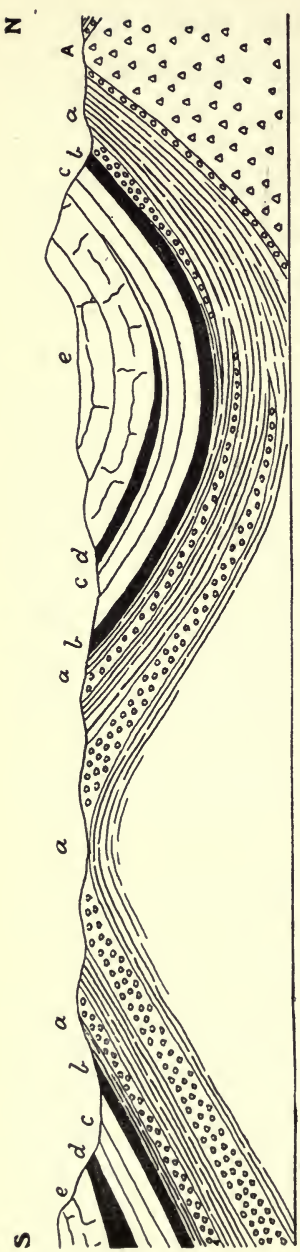


Fig. 100.—Diagrammatic Section from Cader Idris to Snowdon across the Harlech Anticline.
A, Archæan; *a*, Harlech and Llanberis series; *b*, Menevian; *c*, Lingula flags; *d*, Tremadoc; *e*, Ordovician.

from the overlying Lingula flags by the presence of *Paradoxides* and other fossils of the Paradoxidian series.

The **Lingula Flags** are a series of hard tough sandstones and slates passing upwards, towards the top, into softer slates of finer grain with little or no admixture of gritty material. They have been divided into the following groups :—

Dolgelly Beds. Blue and black slates, with *Agnostus trisectus*, *Parabolina spinulosa*, *Peltura scarabæoides*, *Sphærophthalmus*, *Orthis lenticularis*.

Ffestiniog Beds. Blue-grey flags and slates, with *Lingulella Davisi* and *Hymenocaris vermicauda*.

Maentwrog Beds. Yellow and blue-grey slates and flags, with *Agnostus pisiformis*, *Olenus gibbosus*, *O. truncatus*, *O. cataractes*.

The **Tremadoc Series** consists of greyish slates or shales, somewhat flaggy towards the middle. The base is defined by a narrow band crowded with *Dictyonema*, which is found also in Scandinavia and in Russia. The higher beds contain *Angelina Sedgwicki*, *Asaphellus Homfrayi*, *Shumardia pusilla*, *Macrocystella Mariæ* and many other forms.

When next the Cambrian beds appear upon the surface, near the northern border of Caernarvonshire, the total thickness, and especially the thickness of the gritty beds, has considerably decreased. The lower division is formed largely of slates, the Menevian has not been definitely distinguished, and the Tremadoc series and the upper part of the Lingula flags appear to be absent, the Ordovician beds lying directly upon the Ffestiniog group or the lower part of the Dolgelly group.

At the base of the whole system is a band of conglomerate which rests upon the pre-Cambrian rocks. This is followed by a series of bluish and purple, occasionally green, slates known as the Llanberis slates, which are quarried extensively at Bethesda (the Penrhyn Quarry), Llanberis, Nantlle, and other places along the band. At the top of the series, where the slates are green, one or two specimens of a trilobite, *Conocoryphe Viola,* have been found in the Penrhyn Quarry. Above the slates is a series of green and grey, occasionally purple, grits, which are well exposed on Bronllwyd.

The Bronllwyd grits are followed by slaty beds which are almost unfossiliferous, but which probably represent both the Menevian and Maentwrog beds of Merionethshire; and these are succeeded by a mass of flaggy grits with *Lingulella Davisi* and *Cruziana semiplicata,* which clearly correspond with the Ffestiniog series. Above is a small thickness of unfossiliferous slates overlaid directly by the basal grit of the Ordovician.

The Bronllwyd grit evidently represents either the whole or a part of the grits of the Harlech area; and probably the Llanberis slates correspond in part with the more slaty beds below the Harlech grits. But as the base of the series is not visible in Merionethshire, it is not certain whether the grits begin at exactly the same horizon.

South Wales

The Archæan mass of St. David's is completely surrounded by Cambrian beds except at its south-western extremity, where it reaches the sea. Another Cambrian area stretches eastward from the north-eastern corner of St. Bride's Bay; Tremadoc beds are known far to the east at Caermarthen and Llanarthney; and it is probable that in the intervening strip of strongly folded country there may be several exposures of Cambrian rocks which have not yet been separated from the Ordovician strata amongst which they lie.

It is in the St. David's area that they have been most carefully examined, and there the following succession has been made out:—

Lingula Flags . .	Slates, flags, and sandstones generally blue or grey in colour, but sometimes dark. *Lingulella Davisi, Olenus cataractes, Agnostus pisiformis* var. *obesus.*
Menevian Series .	Dark slates and flags. *Paradoxides Hicksi* and *P. Davidis.*

Solva Series . .	Red, purple and grey grits, flags and slates. *Paradoxides Harknessi*, &c.
Caerfai Series . .	Purple, green, and red sandstones and slates, with conglomerate at base. *Olenellus* (?), *Lingulella primæva.*

The **Caerfai** and **Solva Series** consist largely of sandstones, often red in colour, and evidently correspond with the Harlech grits and Llanberis slates of North Wales. In the south, however, chiefly owing to the labours of Dr. Hicks, they have yielded a relatively abundant fauna; and may be divided into a lower division (the Caerfai series) with *Olenellus* (?) and an upper division (the Solva series) with *Paradoxides.* Lithologically, therefore, the Solva series is connected with the preceding Caerfai series; palæontologically with the succeeding Menevian beds.

The **Menevian** deposits are finer in texture and generally darker in colour than the Solva series, but like the latter are characterised by the presence of *Paradoxides, Microdiscus,* &c.

The **Lingula Flags** indicate a recurrence of shallow-water conditions, for they consist largely of flags and sandstones, interstratified with slates. At Trefgarn Bridge the lower division, with *Olenus cataractes* and *Agnostus pisiformis* var. *obesus*, has been definitely recognised; but elsewhere it is generally only the middle division, with *Lingulella Davisi,* which has yielded fossils. The Dolgelly group is supposed to be represented by fine grey shales above the Middle Lingula flags, but the characteristic fossils of this group have not been found.

According to Dr. Hicks the **Tremadoc** series is represented by certain dark slates and flaggy sandstones which occur on Ramsey Island and elsewhere. They contain *Neseuretus*, numerous lamellibranchs and other fossils, none of which are known in the Tremadoc beds of any other area. *Neseuretus* is an early form of *Calymene,* comparable with the Ordovician species *Calymene Tristani,* and it is accompanied by other Ordovician forms. It is now certain that the beds belong to the Arenig series of the Ordovician system.

True Tremadoc beds, however, with *Peltura punctata*, occur near Caermarthen and Llanarthney, where they appear in the axes of some of the anticlines of this strongly folded region.

Welsh Borders and Midlands

Throughout the whole of this area, wherever the Cambrian system is exposed, it consists of an arenaceous or calcareous series below and an argillaceous series above. The former belongs generally to the *Olenellus* zone, but includes sometimes a part of the *Paradoxides* zone. The argillaceous series usually represents the Tremadoc and sometimes the top of the Lingula flags. Nowhere except in Warwickshire is there any sign of the Lower or Middle Lingula flags. The total thickness is always small compared with the development in North and South Wales.

In the Malvern Hills the sandy series is known as the Hollybush sandstone and quartzite. *Olenellus* has not been found in it, but *Kutorgina cingulata*, *Hyolithes* and other forms characteristic of the *Olenellus* zone occur. The lower division of the shaly series is dark in colour and contains *Peltura scarabœoides*, *Agnostus trisectus* and other characteristic fossils of the Dolgelly series. The upper division, often known from its colour as the Grey Shales, contains *Dictyonema*, *Agnostus dux*, *Asaphellus* and other Tremadoc forms.

In the Wrekin district, the base of the Cambrian consists of a series of sandstones and limestones which are best exposed at Comley Quarry. In the lower beds *Olenellus Callavei*, *Kutorgina cingulata*, &c., are found; in the upper beds *Paradoxides Groomi* and many other fossils. Evidently both the *Olenellus* and *Paradoxides* zones are represented. Between the two is a zone with *Protolenus*, a genus of trilobites which in New Brunswick also has been found to form a definite zone between the *Paradoxides* and *Olenellus* series. It is remarkable also that many of the other forms found at Comley are unknown elsewhere in Europe, but occur in America. The argillaceous series, here known as the Shineton Shales, is made of soft and almost unaltered clays, with many beautifully preserved fossils, including *Agnostus dux*, *Asaphellus Homfrayi*, *Shumardia pusilla* and other Tremadoc forms. No Lingula flag fossils are present.

In Warwickshire, near Nuneaton, the succession is more complete. The Hartshill Quartzite at the base consists chiefly of purple grits and shales with a band of red limestone near the top. *Kutorgina cingulata*, *Hyolithes*, &c., occur, and the quartzite clearly belongs to the *Olenellus* series. The shales, best shown in the Stockingford cutting, contain at different horizons (1) *Olenellus*, near the base; (2) an abundant Paradoxides fauna, including several species of *Paradoxides* and many species of *Agnostus*; (3) *Agnostus pisiformis* var. *obesus* and *Olenus truncatus*, characteristic of the Maentwrog series; (4) *Sphærophthalmus* and *Ctenopyge*, genera belonging to the Dolgelly series; and (5) *Dictyonema sociale*. None of the characteristic fossils of the Ffestiniog series have been found, but this may be due to the poorness of the exposures of the flags and shales which lie between (3) and (4), and which might be expected to contain the Ffestiniog fauna.

Lake District

The oldest rocks of the Lake District are the Skiddaw slates, which are in part Cambrian. How much of the slate is Cambrian, and how much of the Cambrian is represented, remains uncertain; but Tremadoc graptolites, such as *Bryograptus* and *Clonograptus*, have been found at Barf, near Keswick.

Scotland

Cambrian beds occupy a narrow strip of country extending from Loch Eireboll to Skye, between the Archæan rocks of the western coast on the one side and the overthrust schists of the Highlands upon the other. They lie unconformably upon both the Torridon sandstone and the Lewisian gneiss, and the surface upon which they rest had been worn down to a plane before they were deposited (Fig. 101).

The base is generally a fine conglomerate or pebbly grit. The lower part of the system is arenaceous, while the upper part consists almost entirely of dolomitic limestones (the Durness Limestone). Lithologically three main divisions are recognised :—

3. Calcareous Series .	Limestones, generally dolomitic, with bands of chert. (Durness Limestone.)
2. Middle Series, partly arenaceous, partly calcareous.	Quartzites and grits with *Salterella*. (Serpulite grit.) Dolomitic shales, mudstones and limestones, with horizontal worm-casts. (Fucoid beds.)
1. Arenaceous Series .	Flaggy grits and quartzites (finer grained towards the top, with vertical worm-casts and burrows, forming the ' Pipe-rock ').

As a whole the deposits clearly indicate a gradual deepening of the sea with minor oscillations or variations in the rate of subsidence. But the depth attained was never great, for even the dolomitic rocks of the upper division are often full of worm-casts.

The **Arenaceous Series** is without fossils excepting the worm-casts and burrows of the Pipe-rock.

In the **Middle Series** *Salterella* and worm-casts are the commonest fossils. But several species of *Olenellus* have been found in the Fucoid beds, and along with them are other forms characteristic of the *Olenellus* series, such as *Kutorgina*, *Hyolithes*, &c. A single specimen of *Olenellus* is also recorded from the Serpulite grit. The whole of the Middle series and of the underlying Arenaceous series must therefore belong to the *Olenellus* or lower division of the Cambrian system.

The first thirty feet of the Durness Limestone is also referred to the same division, on account of the presence of *Salterella rugosa* and *S. pulchella* (which occur in the *Olenellus* beds of North America). But the main mass of the **Durness Limestone** contains a different and very remarkable fauna, entirely unlike any other known in Britain.

Gastropods are the dominant group, chief amongst them being the genera *Maclurea* and *Ophileta*. Lamellibranchs (*Euchasma*), brachiopods, sponges and a few trilobites are also found. None of the species are known in any other British area, but most of those which have been identified occur in North America, Canada and Newfoundland in the 'Calciferous series,' which stands at approximately the same horizon as our Tremadoc. Probably, therefore, a northern sea stretched from Scotland into Canada, and this was colder than the southern sea, or was separated by a barrier.

It is not clear, however, how much of the Durness Limestone belongs to the Tremadoc. One or two of the recorded species belong to the *Olenellus* series, and several are common in the Ordovician beds of America. It is especially remarkable, unless there is some break in the succession, that there is no sign of either the *Paradoxides* or the *Olenus* fauna.

Ireland

Rocks which have usually been supposed to belong to the Cambrian system occur at Bray Head and other localities in the counties of Dublin, Wicklow and Wexford; but the only fossils which have been found are worm tracks and burrows and the peculiar markings known as *Oldhamia*, the organic nature of which has been doubted. No fossils which can be certainly referred to the Cambrian have been found anywhere in Ireland.

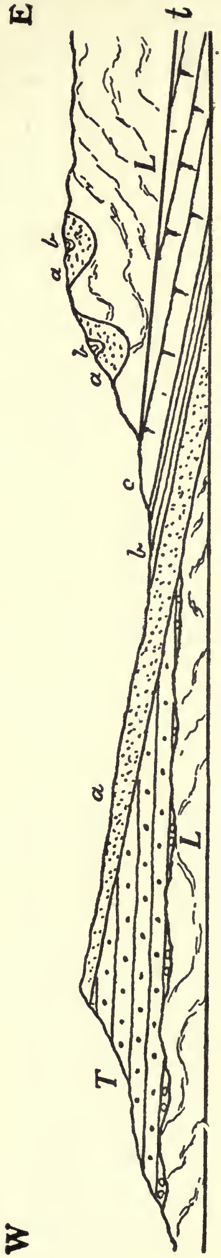


Fig. 101.—Diagrammatic Section across the North-west Highlands.

L, Lewisian gneiss; *T*, Torridon sandstone; *a*, Arenaceous series of Cambrian; *b*, Middle series; *c*, Calcareous series; *t*, Thrust-plane.

Note.—The overthrusting is much more complex than is shown in this diagram.

CORRELATION OF THE CAMBRIAN BEDS

	South Wales	North Wales	Malverns	Shropshire	Warwickshire	North-west Scotland
Shumardia Series	Tremadoc Slates	Tremadoc Slates	Grey Shales	Shineton Shales	Stockingford Shales	Durness Limestone
Olenus Series	Lingula Flags	Lingula Flags	Black Shales			
Paradoxides Series	Menevian Beds Solva Beds	Menevian Beds Harlech Grits and Llanberis Slates				
Olenellus Series	Caerfai Beds		Hollybush Sandstone	Comley conglomerate, limestone and sandstone	Hartshill Quartzite	Serpulite Grit Fucoid Beds Quartzites

CHAPTER XIX

THE ORDOVICIAN SYSTEM

THE Ordovician rocks cover a wider area than the Cambrian. They are found in Cornwall, South Wales, in North Wales and Shropshire, in the Lake District and the Pennine Chain, in the Southern Uplands of Scotland and in several areas in Ireland (Fig. 102).

Three different facies, or types of deposit, may be recognised, viz. the shelly, the graptolitic and the volcanic. In the shelly facies the deposits are more or less sandy and calcareous and generally light in colour, forming now a series of rough and sometimes rather gritty slates, with beds of sandstone, and occasional bands of nodular limestone. Brachiopods and trilobites are the predominant fossils, with corals and cystideans in the calcareous bands, and gastropods and lamellibranchs in the more sandy beds.

In the graptolitic facies the deposits are thinner, and the sediment is finer, forming dark slates or shales, often with bands of chert. Graptolites are the common fossils, with radiolarians in the cherts; but in some of the beds trilobites are abundant. The trilobites, however, usually possess certain peculiar characteristics. They are either blind (e.g. *Trinucleus*, *Ampyx*), or with eyes of extraordinary size (e.g. *Æglina*); and it has been suggested that they lived at such a depth that normal eyes were useless.

In the third or volcanic facies, the rocks consist chiefly of lava-flows, tuffs and agglomerates. In the fragmental beds fossils are sometimes found, occasionally in abundance. The volcanic rocks may be interstratified with deposits of either the shelly or the graptolitic facies, and were no doubt deposited upon the ocean floor.

These three facies do not represent distinct periods. They characterise different areas rather than different epochs, and owe their characters to the conditions under which they were laid down. The shelly facies was the normal type of deposit in moderately shallow water, into which a considerable supply of sediment was brought by rivers from the neighbouring land. The graptolitic facies was formed much more slowly, and was evidently laid down at a greater distance

FIG. 102.—THE ORDOVICIAN SYSTEM.

Much of Cardiganshire, here marked as Ordovician, is occupied by Silurian rocks, but the boundaries between the two systems have not yet been mapped.

from the shore, reached only by the finest of the material derived from the land. The volcanic facies was not confined to any particular depth, but in the British area all the volcanic rocks of this period appear to have been submarine. Marine deposits are often interstratified with them, but never deposits formed upon the land.

As in the case of the Cambrian beds, few estimates of thickness have any value. In North Wales, where the volcanic and shelly facies are well developed, a thickness of 10,000 feet or more has been assigned to the Ordovician system. In the Moffat area, in the south of Scotland, where the graptolitic facies prevails, the base is not seen, but a thickness of about 150 feet represents the upper six or eight thousand feet of the Welsh estimate.

Fauna.—The fauna is much richer in species, and generally in individuals, than that of the Cambrian system. As already remarked, its character varies with the nature of the sediments; but on the whole brachiopods, trilobites, polyzoa and graptolites are the dominant groups.

Of the brachiopods, the genus *Orthis* is the most abundant, both in species and in individuals; but *Plectambonites, Strophomena* and *Leptæna* are also common. Amongst the trilobites *Agnostus* survives from the Cambrian period; *Trinucleus* is confined to this system and ranges from base to summit. *Ampyx*, *Asaphus* and *Ogygia* are particularly characteristic of the lower divisions; *Phacops, Calymene, Homalonotus, Illænus,* and *Cybele* of the higher beds; while the remarkable genus *Staurocephalus* occurs especially at one well-defined horizon.

By far the greater number of the genera of graptolites belong to this system, and the Ordovician genera usually conform to one of two types of structure. Either they are branched and each branch is uniserial (e.g. *Tetragraptus, Didymograptus*), or they are unbranched and the single stem is biserial (e.g. *Climacograptus, Diplograptus*). Simple uniserial forms are rare (*Azygograptus*), and even these differ markedly from the characteristic Silurian genus *Monograptus*. The remarkable form *Phyllograptus* is quadriserial.

Corals are common in the calcareous bands, *Halysites* and *Heliolites* being the genera most often found.

Cystideans are abundant in the upper beds, when these belong to the shelly facies. *Echinosphærites, Caryocystites* and *Hemicosmites* are the most important genera.

Polyzoa are sometimes very abundant. *Monticulipora* is the most widespread genus, while *Ptilodictya* and *Phyllopora* are common in the upper beds.

Gastropods and lamellibranchs are found chiefly in the sandy deposits, where they sometimes occur in great abundance. *Bellerophon*, *Murchisonia* and *Raphistoma* among the gastropods, and *Ctenodonta* and *Modiolopsis* among the lamellibranchs are perhaps the most important.

The cephalopods are represented chiefly by the genus *Orthoceras*, but they are not often found in any great numbers.

Classification of the Ordovician System.—Owing to the great variations in the nature of the deposits, no classification based on lithological characters has more than a local value; and since the fauna varies with the deposits no single palæontological grouping is sufficient. Two parallel classifications are necessary, the one for the shelly facies and the other for the graptolitic. But where the two facies pass laterally into one another there is a certain amount of interstratification, and the two classifications can accordingly be correlated.

The shelly deposits are most conveniently grouped according to the trilobites which occur in them; the graptolitic deposits according to the graptolites. Four series have been recognised, as shown in the following table, in which some of the characteristic trilobites and graptolites of each are given :—

	Trilobites.	Graptolites.
Ashgillian . .	*Trinucleus seticornis.* *Cybele verrucosa.* *Cheirurus juvenis.*	*Dicellograptus anceps.* *Diplograptus truncatus.*
Caradocian . .	*Trinucleus concentricus.* *Phacops apiculatus.* *Asaphus Powisi.*	*Dicranograptus Clingani.* *Pleurograptus.* *Amphigraptus.*
Llandeilian . .	*Trinucleus favus.* *Asaphus tyrannus.* *Ogygia Buchi.*	*Nemagraptus* (=*Cœnograptus*). *Didymograptus Murchisoni.*
Skiddavian or Arenig Series.	*Trinucleus Gibbsi.* *Placoparia.* *Æglina binodosa.* *Ogygia Selwyni.*	*Phyllograptus.* *Tetragraptus.* Extensiform [1] *Didymograpti* and *D. bifidus.*

The Ashgillian and Caradocian are often grouped together under the name of the Bala or Caradoc series.

In the lowest series the trilobites often occur in the same beds as the graptolites; but in the other series they are not usually found together.

South Wales

In most of the Ordovician areas the succession is complicated by the presence of volcanic rocks, which interrupt the regular sequence of fossiliferous deposits. In South Wales, however, the amount of

[1] I.e. *Didymograpti*, in which the two branches open out so widely as to be in line with each other. It should be noted that in this table the fossils are placed in the series to which they belong, but they are not otherwise arranged in any order of succession.

volcanic material is comparatively small; and it will accordingly be convenient to begin with the description of this region.

The Ordovician rocks form a broad band extending eastwards from St. Bride's Bay to Llandeilo; and they occur also farther to the north in the neighbourhood of Builth and elsewhere. But over a large part of South and Central Wales the Ordovician boundaries have not yet been mapped and the distribution of the formation is still unknown.

The **Arenig** or **Skiddavian Series** consists chiefly of blue and black shales or slates, with occasional bands of sandstone in the middle and conglomeratic grits towards the base. The series is in general graptolitic, and when this facies is most completely developed, as it is towards the west, three main divisions can be made out as follows:—

3. Upper Arenig (Llanvirn of Hicks). *Didymograptus bifidus, Placoparia, Æglina binodosa.*
2. Middle Arenig. *Tetragraptus* especially abundant.
1. Lower Arenig. *Didymograptus extensus, Phyllograptus,* various branching graptolites such as *Dendrograptus.*

Towards the east, the lower beds lose their graptolitic character, and *Ogygia Selwyni* (*marginata*) becomes the common fossil.

The **Llandeilo Series,** or **Llandeilian,** consists in part of sandstones and calcareous flags, in part of black shales or slates, and in part of volcanic lavas and tuffs. The sandstones and calcareous flags usually attain their greatest development in the middle of the series, and wherever they occur trilobites become the common fossils, especially *Asaphus tyrannus, Ogygia Buchi* and *Trinucleus favus.* The slates below the flaggy series contain *Didymograptus Murchisoni,* while those above contain *Dicranograptus ramosus,* &c. The volcanic rocks are interstratified with the lower slates and are thickest towards the west, in the neighbourhood of Abereiddy Bay. The volcanic rocks appear to extend downwards into the Arenig series.

The shaly beds of the Llandeilian are continued upwards into the **Caradocian,** with no lithological change. Locally the shales, whether belonging to the Llandeilian or the Caradocian, are known as the *Dicranograptus* shales, on account of the abundance, in places, of the genus *Dicranograptus.* Occasional sandy and gritty beds occur at various horizons, and these contain brachiopods and trilobites. At the top the calcareous matter increases in amount and sometimes forms a definite band of black limestone, which is seen at Robeston Wathen and elsewhere. It contains corals, such as *Halysites* and *Heliolites,* brachiopods, trilobites, &c. It is, however, probable that some of the outcrops which have been referred to the Robeston Wathen limestone belong to the succeeding series.

The **Ashgillian series** consists of a yellowish sandy limestone at the base, followed by a succession of blue-grey and greenish shales with occasional calcareous bands. The whole series belongs to the shelly facies, and is especially characterised by the abundance of cystideans (*Caryocystites*, &c.) and of trilobites (*Trinucleus seticornis*, &c.). The basal limestone, known as the Sholeshook limestone, contains in addition the trilobites *Staurocephalus globiceps* and *Phillipsinella parabola*.

There is probably an unconformity between the Caradocian and Ashgillian series. Not only is there a great and sudden change in the fauna and the character of the deposits, but it appears that the Sholeshook limestone does not always rest upon the same horizon of the *Dicranograptus* shales.

North Wales

In North Wales the Ordovician rocks occupy the Snowdon synclinal and form a broad belt around the landward side of the Harlech dome. They spread northwards into Anglesey, while towards the east they dip beneath the Silurian beds, but rise again to the surface in the Berwyn and the Breidden Hills. In general they lie with a slight unconformity upon the Cambrian beds, but in Anglesey they seem to have overlapped the Cambrian system altogether and to rest directly upon Archæan rocks.

The period was one of great volcanic activity, the centres of eruption lying towards the west. Accordingly, in the Snowdon area and around the Harlech dome, the system consists very largely of volcanic rocks, while in the Berwyn and the Breidden Hills the deposits are chiefly normal marine sediments with only occasional bands of ash. Owing to the general absence of fossils in the volcanic rocks it is often difficult to determine their age with precision, and the difficulty is increased by the irregular and spasmodic nature of the outbursts.

The system begins with an inconstant basal grit, known as the Garth Grit, which rests unconformably upon the Cambrian beds below. This is followed by a series of slates and flaggy beds, sometimes calcareous or mixed with volcanic ash. In the lower beds *Didymograptus extensus* occurs; in the higher and softer shales *Didymograptus bifidus* is found; while in the calcareous and ashy bands, which are best developed towards the middle of the series, *Ogygia Selwyni* and *Calymene parvifrons* are met with. The whole series is clearly of **Arenig** age.

The upper shales are followed immediately by a great thickness of ashes and agglomerates, chiefly andesitic, but becoming more acid and rhyolitic towards the top. On account of their superior hardness these rocks stand up as a ring of high hills around the Harlech dome, the principal summits being Cader Idris, the Arans, Arenig, Manod and Moelwyn. The age of these volcanic beds has not been exactly determined, and it is probable that they do not everywhere begin or end at the same horizon. In the Arenig district the volcanic series rests directly upon shales with *Didymograptus bifidus*, and in its midst is a band of slate with *Diplograptus foliaceus* and other graptolites which are common in Llandeilo beds. In the Moelwyns there are two bands of slate in the midst of the volcanic series, and above are slates with *Climacograptus Schărenbergi* and other Llandeilo graptolites.

It is probable, therefore, that in general the volcanic series belongs to the close of the Arenig period and the early part of the **Llandeilian.** The dark slates which usually overlie the agglomerates may be referred to the later part of the Llandeilo period; but no trace has been found in this region of the flaggy limestones characteristic of the Middle Llandeilo in South Wales.

Farther east, however, in the centre of the Berwyn Hills, Llandeilo limestone with *Trinucleus favus* and *Asaphus tyrannus* has been found. Volcanic rocks also occur, which were probably contemporaneous with those of the west, but little is known concerning them.

The **Caradocian** of North Wales varies greatly in its development, and on this account its limits have not yet been defined. In the Snowdon area it consists very largely of volcanic rocks, chiefly rhyolitic lavas and agglomerates. Near Conway it is represented by *Dicranograptus* shales, similar to those of South Wales. Towards the south and east, around Bala and in the Berwyn Hills, it consists of sandstones and bluish slates with two or three beds of volcanic ash and an occasional band of limestone. Brachiopods, trilobites, &c., are here the common fossils, but there are intercalations of black slate with imperfectly preserved graptolites. Amongst the more abundant fossils may be mentioned *Tetradella complicata*, *Phacops apiculatus*, *Trinucleus concentricus*, *Orthis elegantula*, *Murchisonia gyrogonia*, *Ctenodonta varicosa.*

On the whole, therefore, in the east the Caradocian belongs chiefly to the shelly facies; towards the west it becomes graptolitic and volcanic.

Wherever the **Ashgillian Series** is known in North Wales, it is of the shelly type and closely resembles the corresponding beds of South Wales. The deposits are blue-grey slates, often calcareous and sometimes with definite bands of limestone. No volcanic rocks are known. A limestone with *Staurocephalus* occurs at Rhiwlas near Bala, and is evidently the equivalent of the Sholeshook Limestone of South Wales. Slaty beds with the typical Ashgillian fauna are found in general beneath the Silurian, but owing to the unconformity of the latter. the higher beds of the series are often absent.

In North Wales, as in South Wales, there is a decided break in the succession between the Caradocian and Ashgillian series. This is sometimes due in part to faulting, but the fact that such a break occurs at the same horizon in both areas suggests that the two series must be unconformable.

Shropshire

The eastern continuation of the North Welsh Ordovician is found in Shropshire, where the system is exposed on both sides of the Longmynd, on the west in the neighbourhood of Shelve and Corndon, on the east in a long strip extending from the Severn to the Onny River.

The deposits are similar to those of the Berwyn Hills, but the lower beds are better displayed, while the uppermost beds appear to be absent.

As in North Wales, the base of the system is a siliceous grit, which here forms the ridge known as the Stiperstones. This is overlaid by flags and shales with *Ogygia Selwyni*, *Tetragraptus* and *Phyllograptus*, followed by black shales with *Placoparia* and *Didymograptus*. These beds clearly belong to the **Arenig** series; and towards the top volcanic rocks are interstratified with the shales.

The volcanic beds extend upwards into the **Llandeilo** series. They are followed by (1) shales and flags with *Didymograptus Murchisoni*; (2) flags and limestones with *Asaphus tyrannus* and *Ogygia buchi*; (3) black mudstones with *Nemagraptus gracilis*.

The **Caradocian** is represented by a series of shales, sandstones and limestones with *Trinucleus concentricus*, &c. In the Shelve district they are interstratified with andesitic ashes and agglomerates.

The **Ashgillian** appears to have been overlapped by the succeeding Silurian strata.

In Shropshire, as in North Wales, there were two chief periods of volcanic activity, the first at the close of the Arenig period and the early part of the Llandeilian, the second during the Caradocian period.

Lake District and the Pennine Chain

The greater part of the Lake District north of a line drawn from the head of the Duddon estuary to the upper end of Windermere and thence to the granitic intrusion of Shap Fells, is formed of Ordovician rocks. But the Skiddaw slates are in part of older date. Ordovician rocks are also exposed as inliers at the foot of the Pennine Chain near Cross Fell, Settle, &c.

The oldest rocks of the Lake District (Fig. 103) are known as the

Skiddaw Slates. Only the upper part of these, however, appears to belong to the Ordovician. In these upper slates *Dichograptus*, *Tetragraptus*, *Phyllograptus* and other characteristic Arenig graptolites have been found.

The Skiddaw slates are followed by an enormous mass of basic, andesitic and rhyolitic lavas and agglomerates often called the **Borrowdale Series.** In the Cross Fell inlier dark slates with *Didymograptus Murchisoni* are interstratified with the lower agglomerates, and there can be little doubt that the volcanic series as a whole belongs to the Llandeilian. But the eruptions continued into the succeeding period. Moreover, it is quite possible that older rocks have been included in the series.

The **Caradocian** is represented by calcareous and ashy shales and limestones, with beds of volcanic ash and a band of rhyolitic lava. The total thickness is very much less than in North Wales, and the proportion of limestone is greater; but as in the Berwyn Hills, the fossils are mostly brachiopods and trilobites.

The **Ashgillian Series** begins with a limestone containing *Staurocephalus globiceps* and *Phillipsinella parabola*, evidently corresponding with the Sholeshook and Rhiwlas limestones. The highly fossiliferous limestone of Keisley appears to belong to this band. Above the limestone is a series of blue and grey shales, which are well exposed at Ashgill.

The Caradocian and Ashgillian together have long been known as the Coniston Limestone series.

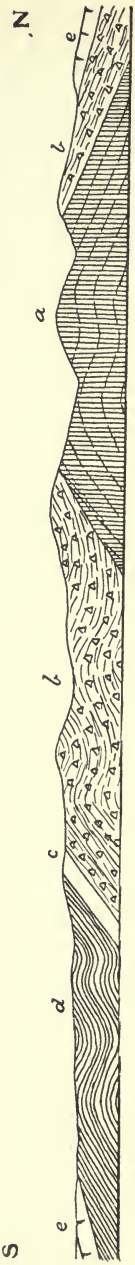


Fig. 103.—Diagrammatic Section across the Lake District.
a, Skiddaw Slates; *b*, Borrowdale series; *c*, Coniston Limestone series; *d*, Silurian; *e*, Carboniferous Limestone.

Southern Uplands of Scotland

The Southern Uplands are formed almost entirely of Ordovician and Silurian rocks, which stretch across the country from sea to sea. Geologically they may be divided into three parallel belts with a south-westerly trend. In the Northern Belt Ordovician rocks predominate. The Central Belt is formed chiefly of the Llandovery and Tarannon series of the Silurian system; but Ordovician beds are exposed in the cores of the anticlines. The Southern Belt consists of the higher Silurian rocks, belonging to the Wenlock and Ludlow series.

Throughout the region the beds are thrown into sharp folds which trend in the direction of the belt and which usually lean over to the south (Fig. 106, p. 337). On account of the resulting constant dip, the thickness was originally very greatly overestimated, but the interbedded graptolitic bands show that this apparent thickness is due to repetition by a series of isoclinal folds.

In general the Ordovician deposits belong to the graptolitic facies, with volcanic rocks interstratified at certain horizons. But towards the north and west the fine black graptolite-bearing shales are gradually replaced by coarser sediments. In the lower part of the system the fine material extends even to Girvan and Ballantrae, but higher up the coarser sediments spread farther and farther to the south. Generally, in the Central Belt the graptolitic deposits predominate, in the Northern Belt the coarser material begins to prevail. The special characteristics of the Northern Belt attain their maximum development in the neighbourhood of Girvan and Ballantrae.

Everywhere the lower part of the **Arenig Series** consists chiefly of basic and andesitic lavas with thin bands of chert and mudstones. These are followed by radiolarian cherts, mudstones and grey shales with bands of tuff. The greatest development of the volcanic rocks is found near Girvan and Ballantrae.

In the Central Belt the **Llandeilo Series** consists of radiolarian cherts and mudstones, followed by black shales with grey and orange-coloured ashy mudstones. The shaly beds are known as the Glenkiln shales, and contain *Nemagraptus gracilis* and other Llandeilo graptolites. But *Didymograptus Murchisoni* has not been found anywhere in the Southern Uplands. It is probable that the Lower Llandeilo, to which this species belongs, is represented by the cherty beds below the Glenkiln shales.

Towards Girvan the Glenkiln shales are replaced by conglomerates and limestones with brachiopods, trilobites, &c. They belong, no doubt, to the Llandeilo period, but the fauna is very different from that of the shelly facies of the Llandeilo series in Wales.

In the Central Belt the **Caradocian** consists of slaty black shales with intercalated pale mudstones. These form the lower part of the 'Hartfell series,' and contain *Pleurograptus linearis, Dicranograptus Clingani, Climacograptus Wilsoni*, &c. Towards the north the sediment becomes coarser, and in the Girvan area the deposits are chiefly conglomerates, grits, flags, mudstones and limestones, with doleritic lavas and andesitic tuffs in the lower part of the series. The Girvan beds contain Caradocian trilobites and brachiopods; but in the interstratified shales lower Hartfell graptolites are found.

The **Ashgillian** is represented in the Central Belt by the upper part of the Hartfell series, mostly barren mudstones with thin bands of limestone and thin seams of black shale. The characteristic graptolites are *Dicellograptus anceps* and *D. complanatus*. In the Girvan area the Ashgillian consists of flagstones and mudstones with *Staurocephalus globiceps*, *Phillipsinella parabola*, *Trinucleus seticornis*, &c. *Dicellograptus anceps* occurs in association with the trilobites.

Ireland

In Ireland the large mass of ancient rock which extends from Dublin Bay to Waterford and Carnsore Point is formed chiefly of Ordovician rocks, though some of the oldest beds are believed to be of Cambrian or even of pre-Cambrian age. Ordovician rocks also occupy a narrow belt extending from Belfast Lough west-south-westward into the southern part of County Leitrim. This is evidently the direct continuation of the Ordovician belt of the Southern Uplands of Scotland. Besides these two principal areas there are several smaller outcrops.

In general the deposits resemble those of corresponding latitudes in Great Britain.

Near Waterford, Llandeilo slates and limestone are followed by *Dicranograptus* shales similar to those of South Wales. Farther north, at Portraine and Kildare, a series of lava-flows, andesitic ash and shales with Caradocian fossils is succeeded by limestones with Ashgillian forms —the succession here being similar to that of North Wales and the Lake District. Towards the west, in Galway and Mayo, a remarkable feature is a calcareous development in the Arenig series containing trilobites similar to those of Sweden and Russia.

In the northern belt the lower beds appear to consist largely of graptolitic shales and radiolarian cherts as in the south of Scotland; but the shelly facies of the Ashgillian series is well developed at Pomeroy, in Tyrone, where it consists of calcareous sandstones, flags, and grits, with graptolitic shales towards the top.

Cornwall

In the extreme south of England, around Veryan Bay, in Cornwall, there is a small Ordovician area. Lithologically and palæontologically it belongs to the French development of the system rather than to the Welsh or English type. It consists chiefly of slates and quartzites, with some volcanic beds and bands of limestone and radiolarian chert. But the folding and faulting is so intense that it is difficult to make out the succession. The quartzite of Perhaver Beach contains *Calymene Tristani*, *Cheirurus Sedgwicki*, &c., and appears to correspond closely with the Grès de May of Normandy, which is approximately on the same horizon as our Llandeilo series.

CORRELATION OF THE ORDOVICIAN BEDS

	South Wales	North Wales	Lake District	Moffat	Girvan	Graptolite Zones
Ashgillian	Upper (with Sholeshook Limestone at base) } Bala Series	Upper (with Rhiwlas Limestone at base) } Bala Series	Upper (with *Staurocephalus* Limestone at base) } Coniston Limestone Series	Upper } Hartfell Shales	Upper } Ardmillan Series	*Dicellograptus anceps* ,, *complanatus*
Caradocian	Lower (= upper part of *Dicranograptus* Shales)	Lower	Lower	Lower	Lower	*Pleurograptus linearis* *Dicranograptus Clingani* *Climacograptus Wilsoni*
Llandeilian	Llandeilo Series	Llandeilo Series	Borrowdale Series	Glenkiln Shales	Barr Series	*Climacograptus peltifer* *Nemagraptus gracilis* *Didymograptus Murchisoni*
Skiddavian	Arenig Series	Arenig Series	Skiddaw Slates (in part)	Radiolarian cherts, mudstones and volcanic tuffs	Radiolarian cherts. shales and volcanic tuffs	*Didymograptus bifidus* ,, *hirundo* ,, *extensus* *Dichograptus*

CHAPTER XX

THE SILURIAN SYSTEM

THERE are many separate outcrops of the Silurian rocks, but geographically they may be grouped as follows (Fig. 104) :—

(1) *Wales and the Welsh Borders.*—In Wales the Silurian beds form a broad band concentric with the Harlech dome, stretching from the mouths of the Conway and the Dee on the north coast to the estuaries of the Dyfi and the Teifi on the shores of Cardigan Bay. But the simplicity of the structure is destroyed by the violent folding to which the area has been subjected, with the result that the Ordovician rocks rise to the surface in many places and interrupt the continuity of the band. Similar folding also brings up the Silurian from beneath the newer beds farther to the east, in the counties which border upon Wales and even in the southern part of Staffordshire.

(2) *The Lake District.*—Silurian beds form practically the whole of the southern portion of the Lake District, excepting where they are covered by later deposits. Small patches are also exposed in several places at the foot of the Pennine Chain.

(3) *South of Scotland.*—The Silurian rocks occur principally in a broad belt which forms the southern part of the Southern Uplands, stretching from the Mull of Galloway to St. Abb's Head. But Silurian beds are also occasionally exposed in the Midland Valley of Scotland, especially in Lanarkshire.

(4) *Ireland.*—A broad triangular area, with its base extending from Belfast Lough to Clogher Head and Balbriggan, and its apex near the Shannon, is evidently the continuation of the belt of the Southern Uplands. Westward the belt disappears beneath the Carboniferous Limestone; but there are smaller outcrops in the western part of Connaught, and several large inliers in Munster.

Except in the south, in County Kerry, Pembrokeshire, Gloucestershire, and in the Mendip Hills, no volcanic rocks are known in

Fig. 104.—The Silurian System.

Silurian rocks also occupy a large part of Cardiganshire, but have not there been separated from the Ordovician.

the Silurian system of the British Isles. But in the sedimentary deposits both a shelly and a graptolitic facies may be recognised. In the shelly facies the deposits are more or less sandy or calcareous, the limestones being of greater thickness and importance than in the Ordovician system. The fossils are chiefly brachiopods, trilobites, corals and crinoids. In the graptolitic facies, where it is typically developed, the sediment is finer and forms black shales, as amongst the Ordovician rocks. Thin-shelled species of *Orthoceras*, as well as graptolites, are abundant in some of these beds.

But, excepting in the lower part of the system, the distinction between the two facies is less marked than in the Ordovician system. Graptolites are common in some of the shales, which are neither black nor fine in texture, and they often occur together with brachiopods and other fossils which are characteristic of the shelly deposits.

Fauna.—In its general characters the fauna is similar to that of the Ordovician system, although many of the genera and most of the species are distinct. Crinoids, however, take the place to a large extent of the cystideans, and cephalopods are considerably more abundant than in the older beds. Towards the top of the system the earliest known remains of fishes occur.

The graptolites are mostly uniserial and belong chiefly to the family Monograptidæ, *Monograptus*, *Cyrtograptus* and *Rastrites* being the most characteristic genera. But some of the Ordovician genera, such as *Diplograptus* and *Climacograptus*, range into the lowest or Llandovery series; and the peculiar biserial genus *Retiolites* occurs at a somewhat higher horizon. Another group of Hydrozoa, namely the Stromatoporoidea, is common in the limestones.

Corals are more abundant than in the Ordovician, and often form a large part of the calcareous bands. *Favosites*, *Halysites*, *Heliolites*, *Acervularia* and *Omphyma* are amongst the common genera; with *Lindstrœmia* and *Petraia* in the Llandovery.

Cystideans are not so common as in the Ordovician system; but crinoids are abundant in some of the limestones (e.g. *Crotalocrinus*).

The earliest British sea-urchins (*Palæodiscus* and *Echinocystis*) occur in the Lower Ludlow. Starfish, both Asteroidea and Ophiuroidea, are found in the Ludlow beds.

Brachiopods are particularly abundant. Most of the Ordovician genera continue into this period, and in addition *Pentamerus*, *Stricklandia*, *Dayia* and other genera appear.

Trilobites are also common. *Calymene*, *Phacops*, *Homalonotus*, *Illænus* and *Encrinurus* are the genera most often met with. The

Phyllocarids are represented by *Ceratiocaris*, *Discinocaris* and one or two other forms. Another group of arthropods, the Eurypterida, becomes of importance in the upper beds, the principal genera being *Eurypterus*, *Pterygotus* and *Slimonia*. The earliest scorpion occurs in the Upper Silurian.

Of the Mollusca, the gastropods and lamellibranchs are probably about as abundant as in the Ordovician system. The cephalopods are more numerous and they all belong to the sub-order Nautiloidea. Most of them occur in the shelly type of deposits. But thin-walled forms (e.g. *Orthoceras primævum*) are common even in the graptolitic shales.

The earliest remains of vertebrates found in the British Isles are the bones and spines of fish, which first appear in the Lower Ludlow, and become more abundant in the Bone-bed of the Upper Ludlow. They include representatives of both the Ostracoderms and the Elasmobranchs.

Classification of the Silurian System.—Although both shelly and graptolitic facies occur, yet except at the top and the bottom of the system the two are interstratified to so great an extent that there is little difficulty in correlating the larger divisions even in widely separated areas.

Only in the lowest division is there any great variation in the nature of the deposits or of the fauna. In this the shelly and the graptolitic facies are totally distinct; they usually occur in separate areas, and the change from the one facies to the other is so rapid that they are seldom found interstratified. The shelly deposits are characterised especially by the abundance of *Pentamerus*; the graptolitic deposits by *Rastrites*, *Monograptus*, *Diplograptus* and *Climacograptus*. The genus *Rastrites* is confined to this division.

The succeeding beds are always shaly, and usually contain graptolites. In some areas limestones and sandstones also occur, but nowhere are they so greatly developed as to exclude the shales. There is, therefore, no difficulty in classifying this part of the succession according to the graptolites. Broadly, they may be divided into a lower series with *Monograptus* of the *priodon* type, and an upper series with *Monograptus* of the *colonus* type.

Finally, in all the areas in which they are found, the upper beds of the Silurian system are more or less sandy; and the amount of arenaceous material increases towards the summit, where they pass upwards into the overlying Old Red Sandstone. No graptolites occur in this division. Brachiopods, &c., are found in the lower part; but the most characteristic fossils are the remarkable Eurypterids.

Omitting all details, the Silurian system may therefore be classified as follows:—

Downtonian	Eurypterid Series	Sandstones with Eurypterids, &c., passing downwards into marine sandstones and shales.
Salopian	Colonus Series	Shales with *Monograptus* of *colonus* type; in some areas limestones and sandstones with brachiopods, &c., occur.
	Priodon Series	Shales with *Cyrtograptus*, and *Monograptus* of *priodon* type; in some areas limestones and sandstones with brachiopods, &c., occur.
Valentian	Pentamerus and Rastrites Series.	Shelly type with *Pentamerus*; graptolitic type with *Diplograptus*, *Climacograptus*, *Rastrites*, *Monograptus*.

Welsh Borders

It was upon the borders of Wales that the Silurian rocks were first reduced to order by Sir Roderick Murchison, and the Silurian system of this area has accordingly become the type with which the corresponding deposits of other regions are compared. Although, however, it is thus the classical Silurian area, it is in some respects abnormal, for there is a much greater development of the shelly facies than in most other parts of the British Isles.

The Silurian rocks lie upon the north-west border of a great triangular area of Old Red Sandstone which covers most of Herefordshire, Monmouthshire and Brecknockshire. They rise to the surface in the Woolhope and Usk anticlines within this area, and upon its eastern border they crop out in the Abberley, Malvern, and May Hills, and also near Tortworth. Farther east, amongst the newer beds, a few small inliers occur in the South Staffordshire coal-field.

Throughout the greater part of this region the shelly facies predominates; but graptolites are by no means rare, and towards the west the deposits gradually become more and more exclusively graptolitic.

The lowest beds are sandy or conglomeratic, occasionally calcareous, and form what is known as the Llandovery series. These are followed by a series of shales and limestones alternating with each other, the shales being sometimes graptolitic and the limestones belonging to the shelly facies. Towards the top the deposits again become sandy and Eurypterids become abundant. Finally, these sandstones gradually grow brighter in colour and pass upwards into the overlying Old Red Sandstone.

The whole succession is as follows:—

Downtonian	Eurypterid Series	Downton Sandstone. Upper Ludlow Shale.
Salopian	Colonus Series	Aymestry Limestone. Lower Ludlow Shale.
	Priodon Series	Wenlock Limestone. Wenlock Shale. Woolhope Limestone.
Valentian	Pentamerus Series	Tarannon Shale. Llandovery Sandstone.

Valentian.—The Llandovery rocks consist chiefly of sandstones and conglomerates, sometimes with so many fossils that they become calcareous. They are evidently shore deposits, and vary greatly in character and in thickness. Sometimes there is an unconformity at the base, sometimes there is a break in the middle of the series. The higher beds overlap the lower, and often rest directly upon the Ordovician rocks. The series is usually divided into Lower Llandovery and Upper Llandovery, but owing to the variability and inconstancy of the deposits these divisions are not very clearly defined. On the whole, *Pentamerus undatus* appears to be characteristic of the lower beds, and *Pentamerus oblongus* of the upper beds. Throughout the series *Pentamerus* is the characteristic fossil, but *Stricklandia* and *Meristina* are also common. Corals such as *Lindstrœmia* and *Petraia*, are sometimes abundant; and trilobites and other fossils are also found.

The Tarannon beds are a series of soft green and purple shales containing very few fossils. Sometimes they rest upon the Upper Llandovery, but often they overlap on to the Lower Llandovery or even the Ordovician. Moreover, the higher beds of the Tarannon shales overlap the lower, so that the whole series is not always present, and the visible thickness therefore varies considerably. They become very thin, or even entirely disappear, towards the east.

Salopian.—The Woolhope Limestone, Wenlock Shale and Wenlock Limestone may be looked upon as a single series, the limestones being nothing more than local developments within the shales. In the eastern outcrops the shales are bluish and belong to the shelly rather than the graptolitic facies. But towards the west they become darker in colour, and graptolites and thin-walled Orthoceratites become the predominant fossils. Several species of *Cyrtograptus*, *Monograptus priodon* and allied forms, *Retiolites*, and *Orthoceras primævum* occur. The Woolhope Limestone lies at the base of the series and occurs chiefly in the eastern outcrops. The Wenlock Limestone forms the top of the series, and is found not only in the east but also on the north-west border of the Old Red Sandstone area in Shropshire. It contains a very abundant fauna, especially corals (*Halysites*, *Heliolites*, *Favosites gothlandica*, *Omphyma*), crinoids (*Crotalocrinus*), trilobites (*Calymene*

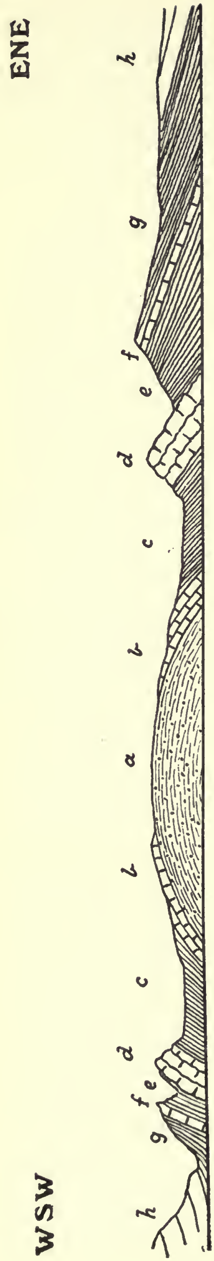


FIG. 105.—SECTION OF THE WOOLHOPE ANTICLINE. (After Murchison.)
a, Llandovery beds; *b*, Woolhope Limestone; *c*, Wenlock Shale; *d*, Wenlock Limestone; *e*, Lower Ludlow Shale; *f*, Aymestry Limestone; *g*, Upper Ludlow Shale; *h*, Old Red Sandstone.

Blumenbachi, *Phacops caudatus*, *Illænus barriensis*), brachiopods (*Atrypa reticularis*, *Strophonella euglypha*).

The Lower Ludlow shales are generally soft sandy shales, greyer in colour than the Wenlock shales. In the eastern part of the area they belong to the shelly rather than the graptolitic facies; but in the west, as for example near Ludlow, they contain graptolites, especially *Monograptus* of the *colonus* type. At the top lies the Aymestry Limestone, with *Pentamerus Knighti*, *Dayia navicula*, &c.

Downtonian.—The Upper Ludlow shales are also soft grey shales, with thin bands of limestone. They contain brachiopods and trilobites, but no graptolites. Towards the top they become more sandy, and include a thin bed, the Ludlow 'Bone-bed,' full of the bones and spines of fish and fragments of Eurypterids.

At the top of the system are the Downton beds, consisting chiefly of sandstones, with some intercalations of shale. The colour is yellowish at the base, but becomes purple towards the top, where the beds pass upwards into the Old Red Sandstone. Eurypterids and remains of fish are the characteristic fossils, but *Lingula cornea* and other shells also occur.

VARIATIONS OF THE SILURIAN DEPOSITS

The descriptions of the remaining districts will be more readily apprehended if a brief summary is given here of the changes which take place in the Silurian deposits as they are followed away from the classical area.

Valentian.—These changes are greatest in the Valentian series, and especially in the Llandovery beds. If we draw a line from Haverfordwest to Llandovery and thence to Welshpool and Llangollen, everywhere upon its south-eastern side the Llandovery belongs to the shelly facies. Generally it consists of sandstones and conglomerates, and is clearly a shore deposit. But upon the western side of the line there is a marked and sudden change. Here the predominating deposits are shales and the dominant fossils are graptolites. In South and Central Wales the change is very abrupt, and takes place in a few miles. In North Wales it is more gradual; the graptolite zones appear one by one towards the west, but the disappearance of the shells is sudden.

Northwards also the shelly facies dies away. In the Lake District the Llandovery is represented chiefly by graptolitic shales, but beds with trilobites and brachiopods occur at intervals. In the Moffat area the whole of the Llandovery consists of graptolite shales.

But the graptolitic sea had a limit on the north as well as on the south-east. At Girvan, in Ayrshire, the Llandovery deposits are conglomerates, sandstones and limestones, with intervening shales. Brachiopods and trilobites are again the common fossils, but graptolites occur in the shaly bands.

The variations of the Tarannon deposits do not follow precisely the same course. Everywhere upon the Welsh borders the Tarannon is thin and shaly; but towards the west it thickens, attaining a thickness near Plynlimmon of about 3,000 feet, and at the same time bands of grit are frequently intercalated in the shales. On the Welsh borders it is usually unfossiliferous, but in the west it contains many graptolite bands.

Towards the north the thickening is less rapid. In the Lake District the Tarannon is represented by about 140 feet of deposit, chiefly of shale with grits above. The principal fossils are graptolites. In the Moffat area the Tarannon series assumes a thickness of several thousand feet, consisting of conglomerates, flags and shales. Fossils are not common, but graptolites occur in some of the beds.

Salopian.—The Salopian series varies less. In the classical area, as already described, it consists of shales with beds of limestone. In the eastern part of this area even the shales belong to the shelly facies, but towards the west they become graptolitic. When followed farther towards the north-west the limestones altogether disappear, but beds of grit come in, and in North Wales attain a very considerable thickness. Brachiopods and trilobites occur in some of these gritty beds.

In the Lake District and the south of Scotland the general character of the deposits is very much the same as in North Wales, and needs no further description here.

Downtonian.—The Downtonian series varies little. Wherever it occurs, whether on the Welsh borders, in the Lake District or in the south of Scotland, it is essentially an arenaceous deposit and was formed in shallow water. In the Lake District the top of the series appears to be absent, and consequently the Eurypterid fauna does not appear.

Central Wales

The greater part of Central Wales is occupied by Llandovery and Tarannon rocks repeated again and again by a series of sharp folds. Later beds appear only on the east, towards the region already described. The change from the shelly to the graptolitic facies which begins in the Welsh borderland is here completed, and the whole succession is graptolitic. In the Llandovery series the change takes place in a remarkably short distance, not more than a few miles separating the exclusively shelly deposits from those which are almost entirely graptolitic.

Valentian.—The Llandovery series consists chiefly of shales and flags, often with a sandstone at the base. At Rhayader the Upper Llandovery rests upon the Lower with a strong unconformity, marked by the development of thick masses of conglomerate. But neither unconformity nor conglomerate has been detected at the Tarannon river about fourteen miles farther north. Graptolites are the common fossils, including *Monograptus gregarius*, *M. Sedgwicki* and many others; but brachiopods, &c., are found in some of the gritty bands.

The Tarannon series is much thicker than on the Welsh borders. It consists of pale mudstones and shales with occasional gritty bands, and becomes purple and green towards the top. There is an overlap at the base of the series, and consequently it rests sometimes on the Lower Llandovery, sometimes on the Upper Llandovery, and sometimes on the Ordovician. The overlap is in general greatest towards the east, and it is probably on this account that the series becomes so thin towards the Welsh borders. Graptolites are the commonest fossils, *Monograptus turriculatus* being one of the characteristic species.

Salopian.—The Wenlock and Ludlow beds are continuous with those of the Welsh borders. They consist of dark slates with intercalated flaggy and gritty bands, but without any definite limestones. The characteristic fossils are Salopian graptolites, with *Orthoceras primævum* and other thin-walled species of *Orthoceras*, and *Cardiola interrupta*; but trilobites, &c., are not entirely absent.

North Wales

In North Wales the graptolitic facies of the Silurian predominates. No limestones are present, but there is a great development of gritty beds, especially in the Wenlock series.

Valentian.—The Llandovery begins with a grit, the Corwen Grit, overlaid by grey slates, which pass up gradually into the green and purple shales of the Tarannon series. The whole thickness is comparatively small. Near the English border the grey slates contain *Pentamerus undatus* and many other brachiopods, and thus belong to the shelly facies. But towards the west the brachiopods disappear and dark bands with Llandovery graptolites (e.g. *Monograptus gregarius*) are intercalated in the series.

Salopian.—The Wenlock series is represented by dark banded slates with beds of grit. The slates contain *Monograptus priodon*, *Cyrtograptus*, *Orthoceras primævum*, &c.; the grits are not usually very fossiliferous, but have nevertheless yielded many of the common Wenlock brachiopods, &c. The amount of gritty material varies greatly, and with it the thickness of the series. Although in Wales generally the shelly facies of the Silurian predominates towards the south and east, and the graptolitic facies towards the north and west, and although this indicates presumably that the land lay towards the south-east, yet these gritty beds increase in thickness towards the north-west and die out towards the south-east. It has, however, been pointed out by Ramsay that the grits are largely felspathic, and he suggests that they were probably derived from the denudation of the Ordovician volcanic centres of Western Wales, which may still have stood above the waters of the Silurian Sea.

The Colonus or Lower Ludlow beds consist of dark flags with siliceous bands, becoming somewhat micaceous towards the top.

The highest beds which have been recognised in North Wales occur on Dinas Bran, near Llangollen. They are somewhat sandy slates, with brachiopods such as *Dayia navicula*, and appear to correspond approximately with the Aymestry Limestone.

Lake District

In the Lake District, as in North Wales, the Silurian system consists chiefly of shales and grits, occasionally calcareous, but without any well-defined beds of limestone comparable with the Wenlock and other limestones of the Welsh borders. Excepting in the higher beds, the graptolitic facies may be said to prevail; but in many of the gritty bands brachiopods and trilobites are found in considerable numbers.

Valentian.—The Llandovery series is represented chiefly by shales and mudstones, with occasional calcareous bands, especially towards the base. The darker shales are graptolitic, the bluer mudstones contain trilobites (e.g. *Phacops elegans*) and other fossils.

The Tarannon series consists of pale-coloured shales with occasional bands of nodular limestone, followed by pale-green and purple grits and shales. Graptolite bands with *Monograptus turriculatus* and *M. crispus* occur in the lower division.

The whole Valentian series, therefore, consists chiefly of shales, and forms a group of beds known as the Stockdale shales.

Salopian.—The Tarannon series is followed, as in North Wales, by a succession of flags or slates with bands of grit. The slaty beds contain graptolites, and, as elsewhere, the lower division is characterised by *Cyrtograptus* and *Monograpti* of the *priodon* type; the upper division by *Monograpti* of the *colonus* type. They represent, therefore, the Wenlock and Lower Ludlow series of the Welsh borders. The more gritty bands, interstratified with the graptolitic deposits, contain trilobites and other fossils. It is in the Colonus series that the grits attain their maximum development.

Downtonian.—The Upper Ludlow series is represented by the Kirkby Moor flags, which are mostly grey calcareous flags, sometimes, however, stained red. Gastropods and lamellibranchs are the commonest fossils; but the Upper Ludlow brachiopod *Lingula cornea* and other forms occur.

South Scotland

In the account of the Ordovician system it was shown that the graptolitic facies prevails in the Central Belt of the Southern Uplands, while towards the north the fine sediment of this facies is gradually replaced by coarser deposits, which contain brachiopods and trilobites. This is true also of the lower part of the Silurian system; but in the upper beds there is no such definite separation of the two facies, and throughout the area shales with graptolites alternate with gritty and conglomeratic beds.

Valentian.—In the Central Belt the Llandovery series is represented by dark graptolitic shales, called the Birkhill shales (cp. Fig. 106). Their total thickness is only about 100 feet; but they can be divided into a number of clearly defined zones by the graptolites which they contain.

In the Girvan area, on the other hand, the corresponding beds are conglomerates, shelly sandstones, limestones, and shales, with a total thickness of about 1,000 feet. The special interest of these deposits is that the limestones and sandstones contain *Pentamerus oblongus* and other fossils characteristic of the Llandovery beds of the Welsh borders; while the shales contain several of the graptolitic zones which have been recognised in the Birkhill shales.

The Birkhill shales of the Central Belt are followed by several thousand feet of massive conglomerates, flags, shales and red mudstones known as the Gala series. They are for the most part barren, but about Selkirk and Melrose they have yielded many fossils, including the Tarannon graptolites *M. crispus* and *M. turriculatus.* It is certain, therefore, that they correspond approximately with the Tarannon shales.

Both towards the south and towards the north the conglomerates and grits thin considerably; and in the Girvan area the corresponding beds are chiefly green and purple mudstones, like the typical Tarannon shales, while the grits are quite subordinate in amount.

Salopian. — The Wenlock and Lower Ludlow beds are represented by a succession of conglomerates, grits and shales, and resemble in general those of the Lake District. They are formed, in fact, of alternations of shelly and graptolitic deposits.

Downtonian. — The higher beds of the system are not known in the Southern Uplands, but they are exposed amongst the later deposits which cover the Scottish Midland Valley. These inliers form two

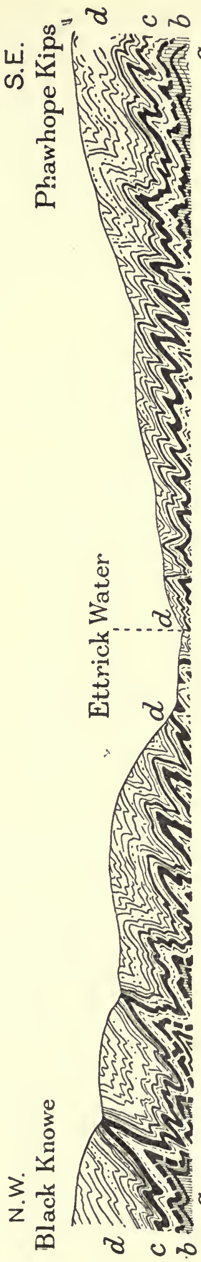


Fig. 106.—Section across Ettrick Water in the Southern Uplands.

(From the *Memoirs of the Geological Survey*, 'Silurian Rocks of Britain,' vol. i. Reproduced by permission of the Controller of H.M. Stationery Office).

a, Glenkiln Shales; *b*, Hartfell Shales; *c*, Birkhill Shales; *d*, Tarannon or Gala series.

groups, one towards the west in Lanarkshire and Ayrshire, the other towards the east in the Pentland Hills. In both areas the deposits consist of shales, flagstones and sandstones, becoming red and green towards the top. Many fossils have been found in them, including eurypterids, phyllocarids, scorpions, fishes, &c., and they clearly represent the Upper Ludlow and Downton sandstone of the Welsh borders. In Lanarkshire they seem to pass up quite gradually into the Old Red Sandstone; but in the Pentland Hills the Old Red Sandstone rests upon their upturned edges.

Ireland

Both the shelly and the graptolitic facies of the Silurian are found in Ireland, the former in the west and the latter towards the north and east.

In the north-eastern area, which is the continuation of the Scottish Silurian belt, Llandovery and Tarannon rocks predominate, and they resemble the Birkhill shales and Gala series of the Southern Uplands. Towards the south of the area, in County Louth, Wenlock beds like those of Scotland have been found. The large inliers of Tipperary and the surrounding counties are also formed, in part at least, of graptolitic beds.

Near the western coast, however, in Galway, Mayo and Kerry, the graptolitic facies disappears and the deposits consist of conglomerates, sandstones, flags and shales. The flags and shales are often calcareous, but no pure limestone is found, and no black graptolitic bands. Brachiopods become the dominant type of fossils. Possibly because the sandy type of deposits extends to a higher horizon than elsewhere, the Llandovery forms *Pentamerus oblongus* and *Stricklandia lens* have been found associated with species which in Wales belong to the Wenlock series.

In the Dingle Promontory the Wenlock beds include a considerable development of rhyolitic lavas and ashes.

CORRELATION OF THE SILURIAN BEDS

		Welsh Borders	North Wales	Lake District	South Scotland	Graptolite Zones
Downtonian	Eurypterid Series	Downton Sandstone Upper Ludlow Shale		Kirkby Moor Flags	Flags and Sandstones of Lanarkshire and the Pentland Hills	
Salopian	Colonus Series	Aymestry Limestone Lower Ludlow Shale	Denbighshire Grits and Flags	Grits, Flags and Slates	Grits, Flags and Shales	*Monograptus leintwardinensis* „ *tumescens* „ *scanicus* „ *Nilssoni* „ *vulgatus*
	Priodon Series	Wenlock Limestone Wenlock Shale Woolhope Limestone				*Cyrtograptus Lundgreni* „ *rigidus* „ *Linnarssoni* „ *symmetricus* *Monograptus riccartonensis* *Cyrtograptus Murchisoni*
Valentian	Rastrites or Pentamerus Series	Tarannon Shale Llandovery Beds	Tarannon Shale Grey Slates Corwen Grit	Stockdale Shales	Gala Series [*Moffat*] Birkhill Shales | [*Girvan*] Conglomerates, Grits, Limestones, Shales	*Monograptus crenulatus* „ *griestonensis* „ *crispus* „ *turriculatus* „ *Sedgwicki* „ *convolutus* „ *gregarius* „ *cyphus* *Diplograptus vesiculosus* *Cephalograptus acuminatus*

CHAPTER XXI

THE DEVONIAN OR OLD RED SANDSTONE SYSTEM

ALTHOUGH it is only here and there that the rocks of the three preceding systems now appear upon the surface, originally the deposits covered the greater part of the British Isles. The Devonian, on the other hand, was discontinuous from the first. It was laid down in isolated basins separated by regions in which denudation exceeded deposition. So far as the area was concerned, the three preceding periods were marine periods ; the Devonian was in part continental.

At present the rocks of this system are found in the following districts (Fig. 107) :—

1. Cornwall and South Devon.
2. North Devon and West Somerset.
3. South Wales and the bordering counties.
4. Cheviot area.
5. Midland Valley of Scotland.
6. Orcadian area (shores of the Moray and Dornoch Firths, Caithness, Orkneys, Shetlands).
7. Argyll.
8. North Ireland.
9. South Ireland.

It must not be assumed, however, that all these areas were originally distinct. In some cases they have been separated by subsequent denudation.

There are two entirely different developments of the system. In Devon and Cornwall the formation consists chiefly of dull-coloured sandstones, slates and limestones, which contain trilobites, brachiopods and corals, and which do not differ in their general character from the Silurian rocks. In the Mendips and north of the Bristol Channel the system is formed of brightly-coloured red and brown sandstones and marls. Neither brachiopods nor corals are found in these deposits, and the arthropods are represented not by trilobites but by the giant Eurypterids. The most important fossils, however, are the remains of plants and of armoured fish.

The first of these two facies is known as the Devonian type, the second as the Old Red Sandstone type. Very few fossils are common

Fig. 107.—The Devonian or Old Red Sandstone System.

to the two, but some of the fish, such as the genus *Pteraspis*, are found both in the Lower Devonian of South Devon and in the Lower Old Red

Sandstone of South Wales. There is, however, but little direct palæontological evidence that the two kinds of deposit were contemporaneous; and it is chiefly from their stratigraphical position that their equivalence is inferred. In Wales the Old Red Sandstone passes downwards conformably into the Silurian, and upwards into the Carboniferous. In Devon and Cornwall the relations of the Devonian to the Silurian are still obscure, but upwards the Devonian beds pass quite conformably into the Carboniferous. In Scotland also the Old Red Sandstone passes upwards into the Carboniferous; and it is highly probable that some of the red beds may belong to that system.

In the north of Russia, deposits of the Old Red Sandstone type lie between the Silurian and the Carboniferous. In Belgium, Germany, France and Southern Europe, rocks of Devonian type occupy a similar stratigraphical position.

There can be no doubt, therefore, that on the whole the Devonian and the Old Red Sandstone are approximately equivalent; but it is by no means certain that the Old Red Sandstone facies ceases everywhere at the same horizon. There is, in fact, a considerable amount of evidence that towards the north it persists into the earlier stages of the Carboniferous.

The Devonian rocks, with their fauna of brachiopods, trilobites and corals, are normal marine sediments. But the absence of any of these forms in the Old Red Sandstone indicates that the red beds were laid down under different conditions. Sometimes they are conglomerates or breccias, sometimes they are current-bedded sandstones, sometimes fine flags showing ripple-marks and sun-cracks; but always they bear evidence that they were formed in shallow water or upon the surface of the land itself. The bright colours also, though by no means universal, differentiate the Old Red Sandstone from any ordinary marine deposits, and are characteristic at the present day of the sediments of the lakes of dry or desert regions. The presence of plants, which in some places are very abundant, points to the immediate proximity of land.

These considerations have led to the belief that while the Devonian rocks were laid down in the open ocean, the Old Red Sandstone was deposited in inland waters, which perhaps were originally arms of the sea cut off by the crumpling of the earth's crust which took place during this period.

The Old Red Sandstone facies is characteristic of Northern Europe, extending southwards to the latitude of the Bristol Channel, and even farther south in Russia. In Central and Southern Europe the Devonian facies alone is found. Hence it may be inferred that a land mass lay in the north, bearing upon its surface sheets of water, while in the south spread the open sea. At times the southern ocean encroached upon the margin of the northern continent, and here to a certain extent the two facies are interstratified. In North Devon, for example, and still more in Russia, red sandstones with remains of fish occur in the midst of slates with brachiopods. In general, however, the limits of the two facies are very sharply defined.

The period was one of violent earth-movements and of great volcanic activity. It was in Devonian times that the overthrusts of the Scottish Highlands and of Western Scandinavia were formed, and most of the folding of the Lower Palæozoic rocks of Scotland, the Lake District and the north of Wales took place. The general direction of the folds is from north-east to south-west, and the result of the movements was the elevation of a mountain range in Northern Europe, of which Norway and most of the British highlands are the worn and broken stumps. This ancient mountain range has been called by Suess the Caledonian Chain.

In Scotland the crumpling of the crust was accompanied by extensive volcanic eruptions; so that in some districts the Old Red Sandstone is formed very largely of lavas and agglomerates. There is no sign of these in South Wales, where the conditions appear to have been more tranquil; but volcanic beds are interstratified with the marine deposits of South Devonshire.

Fauna.—In its general character the fauna of the marine Devonian is similar to that of the Silurian, and many of the Silurian genera still survived.

The most important difference, perhaps, is the entire absence of graptolites, which are last seen in the Ludlow beds. *Stromatopora* and its allies, on the other hand, which are believed to belong to the same class of the animal kingdom, become more abundant.

Corals take a large share in the formation of the limestone bands. Many of the genera occur also in the Silurian rocks, e.g. *Favosites*, *Heliolites*, *Acervularia*; others, such as *Calceola* and *Pleurodictyum*, are peculiar to the Devonian; while some, like *Phillipsastrea*, make their first appearance in these rocks, but range upwards into the Carboniferous.

Crinoids also are common in the limestones, *Cyathocrinus* and *Cupressocrinus* being two of the genera represented.

Brachiopods occur abundantly not only in the limestones, but also in the slates and grits. The genera *Stringocephalus* and *Uncites* are peculiar to the Devonian; of the other forms, *Orthothetes*, *Spirifer*, *Rhynchonella* and *Atrypa* are the most important. Some of the characteristic Carboniferous genera, such as *Productus*, begin to appear in the higher beds.

Mollusca are common in some of the beds. Stratigraphically, the most important are cephalopods belonging to the sub-order Ammonoidea.

Clymenia is entirely confined to this system. The group commonly known as goniatites makes its first appearance, and is represented by the genera *Mimoceras* and *Anarcestes*.

Trilobites are very much less abundant, both in species and in individuals, than in the Silurian rocks. Several of the genera, e.g. *Dalmanites* and *Homalonotus*, show a tendency to develop spines upon the head, thorax or tail—a tendency which in other groups of animals has proved to be a sign of decadence. The commonest forms are *Dalmanites* (*Cryphæus*), *Phacops*, *Homalonotus*, *Pröetus* and *Bronteus*.

A few of the fish which are characteristic of the Old Red Sandstone facies are found also in the marine Devonian. Of these, the genus *Pteraspis* appears to be the commonest.

As a rule, the Old Red Sandstone facies is not very fossiliferous, but in some localities and at some horizons the remains of eurypterids, fish and plants are found in great abundance.

Of the eurypterids, *Eurypterus*, *Pterygotus* and *Stylonurus* are the principal genera.

The fish include representatives of the Elasmobranchii, Ostracodermi, Ganoidei and Dipnoi. The most striking forms are those in which the head and the anterior portion of the trunk is protected by large plates, forming a more or less rigid coat of armour. Amongst these are the genera *Pterichthys*, *Cephalaspis* and *Coccosteus*. Other forms, such as *Holoptychius*, are less abnormal in shape, and bear overlapping scales, but the paired fins are each provided with an axis which is covered with scales.

The plants are mostly lycopods and ferns, including such forms as *Knorria* and *Palæopteris*.

In the higher beds the lamellibranch *Archanodon Jukesi* has been found in several localities. From its general resemblance to the living *Anodon*, it is supposed to have lived in fresh water.

Cornwall and South Devon

It is in this area that the marine facies of the system is most fully developed in the British Isles; but the rocks are so much disturbed by folds and so greatly broken by faults, and the individual beds are often so variable and inconstant, that the determination of the order of succession has proved a difficult task. The deposits are slates, grits, limestones and tuffs; and the fauna is of the typical Devonian type. But some of the characteristic Old Red Sandstone fish, especially the genus *Pteraspis*, occur in considerable abundance at certain horizons. The slates, moreover, are often red or purple in colour, indicating, perhaps, some approach to the conditions which prevailed farther north.

The system is divided into three series, the Lower, Middle and Upper Devonian.

The **Lower Devonian** consists chiefly of slates and grits. The slates are sometimes dark in colour, sometimes green or purple. The grits are variable, but attain their greatest development in the upper part of the series. Volcanic rocks occur, but not to so great an extent as in the Middle Devonian. The fossils are usually distorted. They include *Dalmanites* (*Cryphœus*) *laciniatus*, *Spirifer hystericus* and the peculiar coral *Pleurodictyum problematicum.*

The **Middle Devonian** also consists very largely of slates, but the amount of gritty material is less, while volcanic tuffs and calcareous bands assume a greater importance. Locally, as at Torquay, the limestones attain a considerable thickness and form the greater part of the series. The volcanic rocks occur at various horizons, and reach their greatest development south of Totnes. The lower beds of the series contain *Calceola sandalina ;* the limestones above contain a very abundant fauna, including *Stringocephalus Burtini*, *Uncites gryphus*, numerous corals, &c.

The **Upper Devonian** is formed in part of grey massive limestones with *Rhynchonella cuboides* and several species of goniatites. These are followed by red slates with *Clymenia* and the small crustacean *Entomis serrato-striata.*

North Devon

In the north of Devonshire and the west of Somerset the Devonian system forms a broad belt along the southern shores of the Bristol Channel, extending from Barnstaple Bay on the west to the Quantock Hills on the east. It consists in part of red or yellow sandstones, containing remains of plants and fish, in part of grey, green or purple slates with brachiopods and other marine fossils. Calcareous bands occur, especially in the middle of the formation, but they are nowhere so thick or massive as the limestones of South Devonshire. The Devonian of North Devon is, in fact, an intermediate type, belonging partly to the Old Red Sandstone facies and partly to the true marine Devonian (Figs. 108 and 109).

The strike of the rocks is very regular, and the beds crop out in a series of parallel bands which run from east to west. They are, however, very greatly folded; but as the prevailing dip is towards the south, it has generally been assumed that the oldest strata lie at the northern margin of the belt, and the succeeding beds follow in

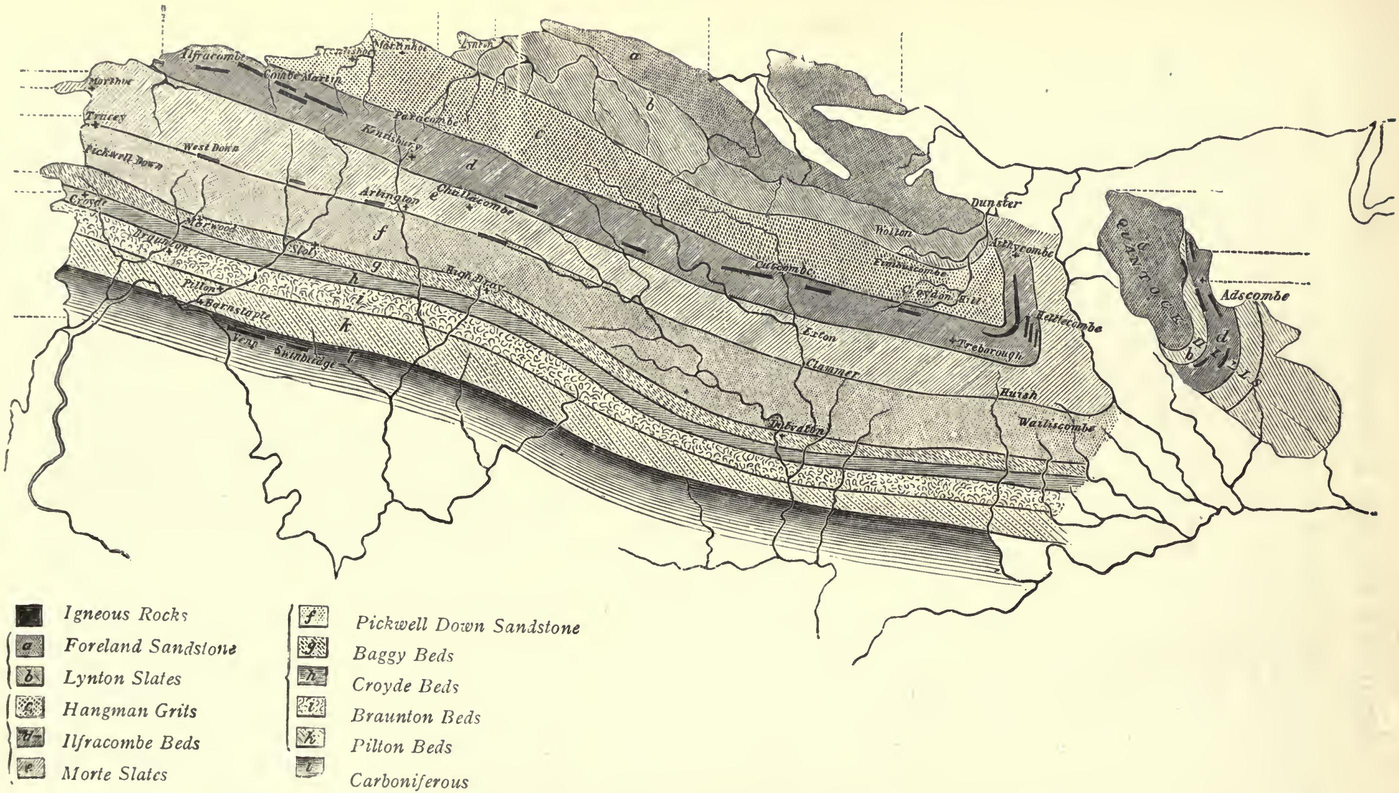


FIG. 108.—GEOLOGICAL MAP OF WEST SOMERSET AND NORTH DEVON. (After Robert Etheridge.)

Note.—The beds called the 'Croyde' and the 'Braunton' beds in this map are usually included in the Pilton series.

regular order towards the south. On this assumption the succession is as follows (in descending order) :—

8. Pilton Beds. Bluish-grey slates with thin bands of limestone and sandstone; very fossiliferous. *Phacops latifrons, Productus prælongus, Spirifer Verneuili.*
7. Baggy Beds. Greenish shales and sandstones. *Ptychopteria damnoniensis, Cucullæa Hardingi*, and plants (*Knorria*, &c.).
6. Pickwell Down Sandstone. Red and purple sandstones. Remains of fish and plants.
5. Morte Slates. Greenish-grey glossy slates, much veined with quartz. *Cryphæus.*
4. Ilfracombe Beds. Grey slates and flags with impure bands of limestone. *Stringocephalus Burtini, Cyathophyllum cæspitosum, Heliolites porosus*, &c.
3. Hangman Grits. Red grits and sandstone. Casts of lamellibranchs and gasteropods in the upper beds.
2. Lynton Slates. Grey and purple slates and grits. *Spirifer lævicosta, S. hystericus, Orthis arcuata.*
1. Foreland Sandstone. Red sandstones and grits. Remains of plants.

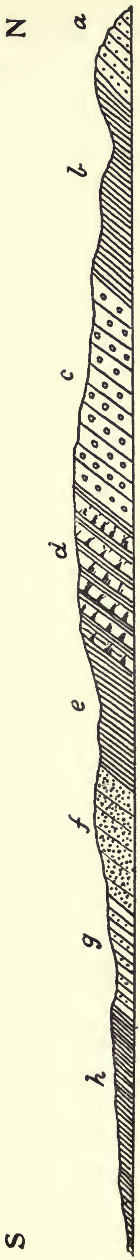


Fig. 109.—Diagrammatic Section across North Devonshire, showing the Apparent Relations of the Beds.

a, Foreland Sandstone; *b*, Lynton Slates; *c*, Hangman Grits; *d*, Ilfracombe beds; *e*, Morte Slates; *f* Pickwell Down Sandstone; *g*, Baggy Beds; *h*, Pilton Beds.

As is shown in this table, the formation consists chiefly of slates with three main bands of red sandstone, viz. the Foreland Sandstone, the Hangman Grits, and the Pickwell Down Sandstone.

It was, however, suggested by Jukes that there was a repetition of beds by means of a fault in the midst of the succession. He believed that the Pickwell Down Sandstone was the same as the Foreland Sandstone, and that the Baggy and Pilton series represented the beds from the Lynton Slates to the Morte Slates. He seems to have looked upon the Hangman Grits as a local sandy development of minor importance.

Jukes' view is not supported by the palæontological evidence, and Etheridge was able to show that the fauna of the beds which follow the Pickwell Down Sandstone is quite distinct from that of the beds which succeed the Foreland Sandstone. According to their fossils, the Baggy and Pilton beds correspond with the Upper Devonian of the Continent, the Ilfracombe beds with the Middle Devonian, and the Lynton Slates with the Lower Devonian. It was therefore concluded that there was no repetition, and that the apparent succession was also the real one.

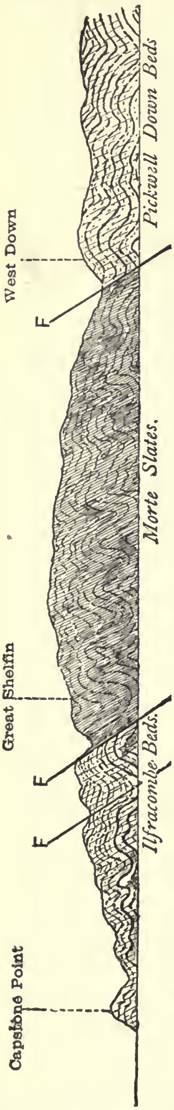


Fig. 110.—Section from Capstone Point, Ilfracombe, to West Down. (After H. Hicks.) Showing the relations of the Morte Slates to the Ilfracombe and Pickwell Down beds.

This view was generally accepted until the last decade of the nineteenth century. Up to that time no fossils had been found in the Morte Slates. In 1890 to 1897, however, Hicks discovered fossils at several localities. The specimens are generally much distorted by pressure, but he identified some as Silurian species and others as Lower Devonian; and he concluded that there is a thrust-fault between the Ilfracombe beds and the Morte Slates (Fig. 110), and probably another between the latter and the Pickwell Down Sandstone. It is not generally admitted that any of Hicks' specimens are Silurian forms; but some, including a species of *Cryphæus*, appear to belong to the Lower Devonian. More recently, however, fossils of Upper Devonian affinities have been found at the western end of the band, and it is probable that the Morte Slates are really a complex of various ages.

So far, therefore, as our present knowledge goes, there is definite palæontological evidence that—

The Baggy and Pilton beds are Upper Devonian.
The Ilfracombe beds are Middle Devonian.
The Lynton Slates are Lower Devonian.

The fossils in the sandstones are scarcely sufficient to determine their horizon.

The succession is probably more complex than it appears, and much remains to be done before the true relations of the beds can be established.

South Wales and the Welsh Borders

North of the Bristol Channel the marine facies has entirely disappeared, and the system is formed of red, brown and yellow sandstones, flags, &c., with remains of fish, eurypterids and plants. In Wales and the bordering counties these rocks cover a large triangular area, with its base on the western side of the Severn Valley and its apex in Pembrokeshire. The lower beds pass gradually and conformably into the Upper Silurian, and the upper beds into the Lower Carboniferous. There is no evidence of any break in the midst of the formation, nor is there any sign of volcanic activity. The region appears to have been one of continuous deposition without disturbance of any kind, and in this it differs from all the other British areas of Old Red Sandstone.

On account of this continuity of deposition and the general rarity of fossils, the divisions which have been adopted have no more than a local value. The lower part consists of red and variegated marls, with lenticular beds of red or grey limestone, sometimes known as cornstone ; and it contains eurypterids and fish of the genera *Pteraspis*, *Cephalaspis*, &c. The upper part is formed chiefly of red, brown and yellow sandstones and conglomerates. *Holoptychius* is found in these beds, and the lamellibranch *Archanodon Jukesi*. Towards the top of the series the exceptional occurrence of *Conularia* and *Serpulæ* points to occasional incursions of the sea.

Scotland

In Scotland the Old Red Sandstone is usually divided into a Lower and an Upper Series, separated by a strongly marked unconformity. Recent researches, however, tend to show that the lower part of the Lower Series belongs to the Silurian, and a part at least of the Upper Series to the Carboniferous. It appears, therefore, that the conditions necessary for the formation of deposits of the Old Red Sandstone type began earlier and ended later than in South Wales. But since, during this period, the land lay towards the north and the sea towards the south, the difference is no more than might be expected. At the beginning of the period the sea retreated southwards; at the close it advanced northwards.

The Cheviot Area

In this region the Old Red Sandstone lies chiefly on the Scottish side, but it also extends south of the border into Northumberland. It rests unconformably upon the folded Silurian rocks, and consists of red sandstones and marls, together with beds of lava, tuff and agglomerate. In the Cheviot Hills themselves the volcanic rocks attain a thickness of a couple of thousand feet. They are mostly andesitic, and commonly contain a rhombic pyroxene. No fossils have been found excepting remains of plants and eurypterids, but the whole series is referred to the Lower Old Red Sandstone.

Resting unconformably upon these beds there is a second series of red sandstones and marls, with a basement conglomerate or breccia. It is uncertain how much of these belongs to the Old Red Sandstone and how much to the Carboniferous. But *Palæopteris hibernica* and scales of fish have been found in the lower part.

Midland Valley of Scotland

The Old Red Sandstone and the succeeding Carboniferous beds form the lowland belt which stretches from north-east to south-west across the centre of Scotland, between the Highlands on the north and the Southern Uplands on the south. The middle of the belt is occupied by the Carboniferous deposits, and the Old Red Sandstone appears along its northern and southern margins.

In this area—the 'Lake Caledonia' of Sir Archibald Geikie—the Old Red Sandstone is divided into two series by a strong unconformity.

The **Lower Series** consists of red, brown, yellow and grey sandstones, flags, shales and conglomerates, with occasional bands of limestone. In the midst of the series there are massive and extensive beds of lava, tuff and agglomerate, which, on account of their hardness, stand up as ridges, forming, for example, the Ochil and Sidlaw Hills. As in the Cheviots, the volcanic rocks are generally andesitic.

When the base of the series is exposed, as in the Pentland Hills, it generally rests unconformably upon the Silurian rocks below. But near Lesmahagow, in Lanarkshire, there is apparent conformity, and the uppermost beds of the Silurian belong to the Red Sandstone type. There is here no certain line of demarcation between the two formations, but the boundary is drawn at a band of conglomerate which may represent an unconformity. Below this line the pebbles in the deposit are derived from the Highlands; above it, from the Southern Uplands

Fossils are not usually abundant, but fish, eurypterids and plants occur; and amongst the fish are the genera *Cephalaspis* and *Pteraspis*, which are also found in the Lower Old Red Sandstone of Wales.

The **Upper Old Red Sandstone** lies unconformably upon the Lower, and frequently overlaps it so as to rest upon still older rocks. It consists of red sandstones, clays, marls, conglomerates and breccias, but includes no volcanic rocks such as those which form so striking a feature of the Lower Series. Remains of fish are again the principal fossils, but they are of different genera, *Coccosteus* and *Holoptychius* being amongst the characteristic forms.

These beds pass upwards into the Lower Carboniferous, and it is probable that some part at least of the red beds should be included in that system ; but in the present state of our knowledge it is not possible to define the limits of the two formations.

Orcadian Area

The Old Red Sandstone forms a coastal strip around the shores of the Moray and Dornoch Firths ; it spreads over the greater part of Caithness and the Orkneys, and occurs also in the Shetland Isles. As in the rest of Scotland, there are two divisions separated by an unconformity.

The **Lower Old Red Sandstone** lies upon a denuded and uneven floor of crystalline schists, granite, &c. Where the deposits rest upon this floor, or abut against its slopes, they are coarse and conglomeratic ; but elsewhere they are for the most part fine-grained, sandy, clayey, calcareous or bituminous flags, often showing sun-cracks and ripple-marks. Clearly they were laid down in tranquil waters, and the conglomerates were formed as beaches. Towards the top of the series the deposits become more siliceous and form definite sandstones.

Excepting in the Shetlands, there are only one or two sporadic outbursts of volcanic rock. In some places the remains of fish are very abundant. *Cephalaspis* occurs, but for the most part the genera are different from those which are found in the Lower Old Red Sandstone of the Midland Valley or of Wales. It is probable, therefore, that the deposits are not of the same age, and that the beds which are called Lower Old Red Sandstone in the Orcadian area may really belong to the middle of the period.

The **Upper Old Red Sandstone** consists of yellow and red sandstones resting unconformably upon the lower division. They contain *Holoptychius*, *Coccosteus* and other fish. In the Orkneys there are beds of lava and volcanic ash near the base of the series, the only known example of volcanic action in the Upper Old Red Sandstone of Great Britain.

Argyll

There is a small area of Old Red Sandstone at Oban, which appears to belong to the lower division of the system. It consists of andesitic and trachytic lavas and tuffs, sandstones, shales and conglomerates.

Its chief interest lies in the fact that these beds are invaded and metamorphosed by intrusive masses of granite, showing that some of the younger granites of the Highlands belong to this or a later period.

Ireland

The Irish areas of Old Red Sandstone may be divided into two groups. In the north is the continuation of the Caledonian area, most conspicuously developed in the counties of Tyrone and Fermanagh. In the south the Old Red Sandstone appears to be the continuation of the Welsh deposits, and forms the principal heights and mountains of Munster.

But the Old Red Sandstone of the south of Ireland differs considerably from that of Wales. It consists of two distinct series separated by an unconformity. The Lower Old Red Sandstone is formed of purple, grey and green slates, grits, and conglomerates, which in the Dingle Promontory follow the Ludlow beds conformably. They have yielded no fossils except such as have been derived from the Silurian rocks below.

The Upper Old Red Sandstone, which rests unconformably upon the lower division, appears to consist normally of red conglomerates at the base, followed by brown and yellow sandstones with red and green shales. But the sandstones and shales overlap the conglomerates, and sometimes lie directly upon the older rocks. Towards the top they contain *Archanodon Jukesi*, remains of *Coccosteus* and other fish, *Palæopteris hibernica*, &c. In Waterford and Kilkenny these beds are known as the Kiltorcan beds, and they are evidently the equivalents of the upper part of the Old Red Sandstone of Wales. They pass upwards conformably into the Lower Carboniferous.

In the north of Ireland the largest area of Old Red Sandstone stretches from Lough Erne to the Ordovician rocks of Pomeroy. It consists chiefly of red and purple conglomerates and sandstones, which are referred to the lower division of the system.

CHAPTER XXII

THE CARBONIFEROUS SYSTEM

The Carboniferous rocks of England (Fig. 111) are affected by two systems of folds and faults, running respectively from north to south and from east to west. By these folds they are thrown into a series of basins, which in some cases still remain connected but in others have been completely isolated by subsequent denudation.

In the north of England the dominant fold is an anticline, which runs from Derbyshire northwards and ultimately becomes a fault. In consequence of this the Carboniferous system forms a broad belt extending down the middle of the country from Berwickshire to Derbyshire.

In the Midland plain the Carboniferous beds are to a large extent concealed by newer deposits, but through these they appear occasionally as inliers. Upon the western margin of the plain they crop out in a narrow strip resting against the old rocks of the Welsh borderland; and several outliers occur still farther west.

In the south, the east-west folds begin to prevail. In South Wales the Carboniferous beds form an elongated basin with its axis running from east to west. They form another basin in the Forest of Dean, and a somewhat complicated system of folds in Gloucestershire and Somerset, including the Bristol coal-field and the Mendip Hills.

In Devonshire the Carboniferous strata occupy a broad syncline between the Devonian rocks of the north and south of the county.

In Scotland the Carboniferous beds form a large part of the Central Lowlands, extending completely across the country from the Firth of Forth to the coast of Ayr.

Carboniferous rocks cover the greater part of Ireland. They form almost the whole of the central plain, and although interrupted by the appearance of older rocks in the cores of the anticlinal folds, they stretch south-westwards through Munster. Only in the north and the south-east of the country are there any extensive areas from which the Carboniferous beds have been entirely removed.

FIG. 111.—THE CARBONIFEROUS SYSTEM.

The Carboniferous system of the British Isles may be divided into two series. In the earlier part of the period marine conditions prevailed, and great masses of limestone were formed. In the latter part the area became land, and deposits of sandstone, shale and coal were laid down. It was formerly customary to divide the system into—

Coal Measures,
Millstone Grit,
Carboniferous or Mountain Limestone;

but it was recognised that terrestrial conditions began much earlier in the north than in the south, and that in Scotland even the lower division contains fresh-water beds and seams of coal. So marked, however, in general is the difference between the beds below and the beds above the Millstone Grit that the former were commonly spoken of as the Lower Carboniferous, while the Millstone Grit and the Coal Measures were grouped together as the Upper Carboniferous.

It was doubtful, however, whether the beds known as the Millstone Grit were everywhere at the same horizon, and it has since been proved that sandstones of various ages have been included under this name. The division into Lower and Upper Carboniferous is still retained, but the base of the Millstone Grit can no longer be accepted as the dividing-line, and even now there is not complete agreement as to the limits of the two divisions.

A.—LOWER CARBONIFEROUS OR AVONIAN.

The Lower Carboniferous forms the rim of all the Carboniferous basins excepting those of the Midlands; it forms also the central and broadest portion of the belt which runs from Berwick to Derby; it occupies a large part of the Central Lowlands of Scotland; and it covers nearly the whole of the Irish plain.

Typically it is a limestone formation, and its most prominent member is commonly known as the Carboniferous or Mountain Limestone. But towards the north it loses its calcareous character and becomes a succession of sandstones and shales with only subordinate beds of limestone. In the Midland plain it is absent or much reduced in thickness. In Devonshire it is represented chiefly by shales and cherts.

Fauna.—The fauna of the Lower Carboniferous is rich and varied in character. Corals, brachiopods and crinoids are the most abundant forms, the limestones being made up to a very large extent of their remains.

Of the corals, the genera *Lithostrotion*, *Lonsdaleia*, *Clisiophyllum*, *Cleistopora*, *Zaphrentis*, *Cyathophyllum* and *Syringopora*, are amongst the most important. The first three are confined to this system.

The crinoids include a number of genera which survived from the preceding period, and also *Actinocrinus*, *Amphoracrinus* and *Woodocrinus*, which appear for the first time. Another group of echinoderms—the Blastoidea (e.g. *Granatocrinus*)—attain their maximum development in these rocks; and there are several genera of echinoids, such as *Archæocidaris* and *Palæechinus*.

Of the brachiopods, *Productus* (*P. giganteus*, *P. semireticulatus*) is the most characteristic genus, although it is not confined to these beds. Other important genera are *Spirifer* (*S. striatus*), *Rhynchonella* (*R. acuminata*), *Athyris*, *Terebratula* (*T. hastata*).

Lamellibranchs and gastropods are both abundant. Amongst the former the genera *Conocardium* and *Posidonomya* (*P. Becheri*); amongst the latter the genus *Euomphalus* (*E. pentangulatus*) may be mentioned.

The Cephalopoda include straight forms such as *Orthoceras* and *Actinoceras*, and also several genera of goniatites such as *Glyphioceras*.

The last survivors of the trilobites are found in these beds; but they are not common, and they are generally small. *Phillipsia*, *Griffithides* and *Brachymetopus* are the genera most often met with; but a few other forms also occur occasionally. Another group of Crustaceans, viz. the Schizopoda, is abundantly represented in the Carboniferous of Scotland.

Fish remains, especially teeth and spines, are common. They include elasmobranchs (e.g. *Psammodus*), ganoids and Dipnoi, but no ostracoderms.

The first amphibians occur in the Lower Carboniferous. They belong to the group of Labyrinthodonts.

In the brackish and fresh-water deposits of the north, plants and lamellibranchs are found, some of which do not appear in the south until the Coal Measure period.

Classification of the Lower Carboniferous.

The Lower Carboniferous beds change in character as they are traced across the country, and particularly when they are followed from south to north. In Devonshire the series consists of radiolarian cherts, calcareous shales, and black limestones. In the Bristol and South Wales area it is formed mainly of limestone, with shales at several horizons. Towards the north it thins out rapidly, till in South Staffordshire and Warwickshire it disappears entirely, and the Upper Carboniferous rests directly upon the older rocks. But it reappears in Derbyshire, where it is again formed chiefly of massive limestone, showing a thickness of more than 1,500 feet, although the base of the series is not exposed. Along the Pennine Chain beds of sandstone and shale appear in the limestone, and rapidly increase in thickness, while the amount of limestone is reduced, until in Northumberland the series as a whole consists chiefly of sandstones and shales, with subordinate limestones and an occasional seam of coal. In Scotland the shallow-water character of the deposits is still more strongly marked, some of the beds containing fresh-water fossils, and the seams of coal being of considerable thickness and importance.

From this general description it will be evident that during the period of the Lower Carboniferous the principal area of land lay to the north, in Scotland, and from there the sea deepened towards Derbyshire. Across the Midlands a ridge of land stretched from east to west, and against this ridge the Lower Carboniferous deposits thinned out on both sides; but south of it the sea again deepened towards Bristol. At one time it was supposed that the radiolarian cherts of Devonshire indicated still deeper water in the south; but radiolarian cherts are often interbedded with shallow-water deposits, and cannot be considered as conclusive evidence of deep-sea conditions.

The lithological changes just described, indicating differences in the depth of the sea, are accompanied by changes in the character of the fauna. Consequently, there has always been considerable difficulty in correlating the beds of different areas, and it was not until 1904 that a zonal succession in the Lower Carboniferous was established.

It was in the Bristol area that a clear and definite palæontological classification was first successfully attempted, and accordingly the Lower Carboniferous of Bristol has become the type with which the succession in other areas is compared. The zonal divisions are based upon the corals and brachiopods, which are the most abundant fossils, and five zones are recognised, which for brevity are often referred to by letters, as shown in the following table (in descending order):—

D. Dibunophyllum zone.
S. Seminula zone.
C. Syringothyris zone.
Z. Zaphrentis zone.
K. Cleistopora zone (with Modiola phase, M., at its base).

The 'Modiola phase' is characterised by the presence of *Modiola* *lata*, and is looked upon as a shallow-water facies of the Cleistopora zone.

Each of these zones is further divided into subzones, which are denoted by small numerals or letters affixed to the symbol for the zone. Thus, K_1 indicates the lower division of the Cleistopora zone, and K_2 its upper division.

At Bristol D_2 is immediately followed by the Millstone Grit, and was believed to be the top of the Lower Carboniferous; but on applying the classification to other areas it was found that a series of beds with a different fauna intervened between D_2 and the Millstone Grit. This higher series is commonly considered as a higher subzone of D, and is of particular interest, partly because it lies at the upper limit of the Lower Carboniferous, and partly because its character, both lithological and palæontological, varies considerably. In some areas its fauna is a later development of that which is found in D_2 at Bristol; in other regions it is characterised by the presence of *Cyathaxonia*, a coral which is unknown at Bristol; while in many places the predominant fossils are goniatites and lamellibranchs, the latter including *Posidonomya becheri*. Thus there are three distinct facies, the first of which, from its resemblance to the Bristol type, may be looked upon as normal, while the other two may be called the Cyathaxonia and Posidonomya facies. Their periods, indeed, were not absolutely coincident, but they overlapped one another to a greater or less extent. The symbols applied to these facies are D_3, D_y,[1] and P respectively.

The Posidonomya facies corresponds with a part of the Pendleside series of Lancashire and Derbyshire, which has been placed in the Upper Carboniferous; but the fact that at Loughshinny, in County Dublin, Cyathaxonia beds are interbedded with Posidonomya beds shows that the two faunas were in part contemporaneous. It is in this connection that there is a difference of opinion as to the limits of the Lower and Upper divisions of the Carboniferous. The Pendleside beds mark the entrance of the Upper Carboniferous fauna; the Cyathaxonia beds and D_3 mark the end of the Lower Carboniferous fauna. Some authors place the whole of the Pendleside series in the Lower Carboniferous, while others include it in the Upper Carboniferous.

[1] The position of the Cyathaxonia facies relatively to the Bristol sequence was the first to be determined, and accordingly the symbol D_3 was originally applied to it; the normal facies, upon its discovery at a later date, was called D_y. But since, of these two symbols, D_3 naturally suggests a closer connection with D_2, they are now transposed by some authorities.

Variations of the Lower Carboniferous

Devonshire.—The Carboniferous rocks of Devonshire consist of shales with bands of chert, limestone and impure coal. The latter is locally known as culm, and the whole succession is often called the Culm measures. The rocks are greatly folded, but it is now clear that the Culm measures may be divided into a lower division belonging to the Lower Carboniferous and an upper division corresponding with the Upper Carboniferous of other districts.

The lower division occupies a comparatively small area upon the margins of the Devonian syncline, and includes two distinct series of beds, the one cherty and the other calcareous.

The cherty series, known as the Coddon Hill series, consists of thin-bedded, hard cherty rocks with intermediate beds of light-coloured siliceous shale. The cherts are formed of radiolaria, and several species of trilobites and numerous diminutive brachiopoda have been found in this series.

The calcareous series consists of black shales and limestones, with *Posidonomya Becheri, Glyphioceras spirale, G. crenistria*, &c.

The precise horizon of the Coddon Hill beds is uncertain, but the calcareous beds clearly belong to the Pendleside series, and will be placed with the Upper or the Lower Carboniferous according to the view taken as to the position of that series.

In the neighbourhood of Launceston there are two bands of radiolarian chert, and between them lies a series of black shales, with limestone lenticles and thin bands of grit. Sheets of lava also occur within the shales and above the upper chert.

Bristol and South Wales.—The Lower Carboniferous is admirably exposed in the gorge of the Avon (Fig. 112) at Bristol. It consists of massive limestone, with shales at the base, towards the middle, and again at the top. Lithologically the following divisions have long been recognised, and their relations to the palæontological zones are shown in Fig. 112.

Upper Limestone Shales, with the Upper Limestone in their midst.
Middle Limestone.
Middle Limestone Shales.
Lower Limestone; usually encrinital, a band of oolitic limestone (the 'Gully Oolite') at the top.
Lower Limestone Shales.

When the Lower Carboniferous is followed into South Wales the general succession remains the same, but with certain differences of considerable interest. There are three Modiola phases, one at the base, a second in the middle of the Syringothyris zone, and a third at the top

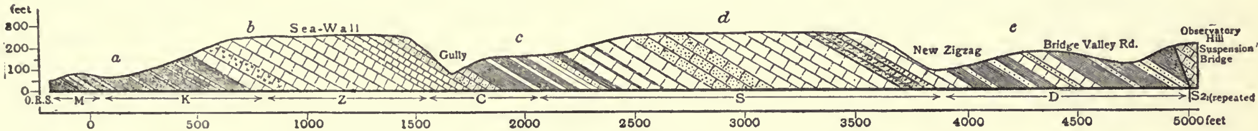


FIG. 112.—SECTION IN THE AVON GORGE. (After Dr. A. Vaughan.)

a, Lower Limestone Shales; *b*, Lower Limestone; *c*, Middle Limestone Shales; *d*, Middle Limestone; *e*, Upper Limestone Shales with Upper Limestone. The letters M, K, &c., refer to the palæontological classification, for which see p. 363.

of the Seminula zone. *Cyathaxonia* occurs at the top of D_2, while the beds above D_2 consist of radiolarian chert, followed by shales with *Posidonomya becheri*, *Glyphioceras reticulatum*, and other fossils belong to the P facies.

Another interesting feature is that as the beds are traced towards the west, along the southern border of the coal-field, the Syringothyris zone gradually disappears, and at last the Seminula zone rests directly upon the Zaphrentis zone. This is apparently due to an unconformity with accompanying overlap which, in the east, begins in the middle of the Syringothyris zone.

Midlands.—When traced northwards from Bristol the Carboniferous Limestone rapidly decreases in thickness. At first this is due mainly to the fact that the upper beds are replaced by arenaceous deposits. In the Forest of Dean, for example, the limestone includes only the representatives of the Cleistopora, Zaphrentis, and Syringothyris zones, with, possibly, a part of the Seminula zone, and it is followed immediately by a sandstone which was supposed to be the Millstone Grit. There is said to be no unconformity, and hence the sandstone must represent, more or less completely, the higher part of the succession.

In the Clee Hills, in Shropshire, a similar grit follows close upon the Zaphrentis zone, the arenaceous facies thus beginning at an earlier date than in the Forest of Dean.

Farther north the Lower Carboniferous disappears entirely, and in parts of the South Staffordshire and Warwickshire coal-fields the Upper Carboniferous rests directly upon Silurian or older beds.

Derbyshire and North Wales.—But the series again thickens rapidly towards the north, and in Derbyshire (Fig. 113) it is represented by some 1,500 feet of massive limestone, with occasional bands of basaltic lava and tuff, which are known locally as toadstones. The beds form a broad anticline; but even in the centre of the arch the base of the series is not exposed. The whole of the limestone, so far as it is visible, belongs to the Dibunophyllum zone, with the Cyathaxonia subzone at the top. Above the latter come the black shales and limestones of the Pendleside series. In general there is a passage from the one to the other, but locally they are separated by an unconformity.

In North Wales the succession is very similar, except for the absence of the volcanic beds. The base, however, is well exposed. Sometimes it consists of red sandstones and conglomerates, which were formerly supposed to belong to the Old Red Sandstone; but usually the limestone rests directly upon Silurian or Ordovician beds. It is possible that a very small thickness may belong to the Seminula zone; but the rest, as in Derbyshire, forms the Dibunophyllum zone, with the Cyathaxonia subzone, followed by the Pendleside series, at the top.

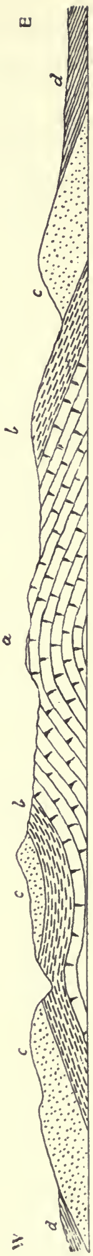


FIG. 113.—DIAGRAMMATIC SECTION ACROSS DERBYSHIRE.
a, Carboniferous Limestone; *b*, Pendleside Series; *c*, Millstone Grit; *d*, Coal Measures.

North Pennines and the Lake District.—As the series is traced along the Pennine Chain, the limestone becomes broken up by beds of shale and sandstone. But for some time it may still be divided into a lower part, consisting largely of massive limestones, and an upper portion in which shales and sandstones play a larger part, but which includes several persistent beds of limestone. This upper portion has long been known as the Yoredale series, and its relations to the Pendleside series form one of the principal problems of the area. Originally the two were supposed to be equivalent; but the Yoredale series contains a coral and brachiopod fauna, which is, in fact, the D_3 of the palæontological classification already given, while the Pendleside series is characterised by lamellibranchs and goniatites, which are more closely related to the fossils which are found in the marine bands of the Upper Carboniferous. Hence it was considered that the Pendleside beds must lie at a higher horizon than the Yoredales, and they were placed in the Upper Carboniferous. More recently, shales with *Posidonomya*, *Glyphioceras diadema* and *G. reticulatum* have been found in the Yoredale series, and some authors have again concluded that the two series are identical.

The difficulty arises from the fact that the two faunas lived under different conditions, and those conditions began and ended in different places at different times. Thus, while the Pendleside type of fauna persists into the Coal Measures, it may begin, as it appears to do in Scotland, far below the top of the Lower Carboniferous.

Even where the rocks are calcareous, and brachiopods and corals are the

PLATE XXXIII

Photo by H.M. Geological Survey.

CLIFF OF COLUMNAR BASALT IN THE TUFF AND AGGLOMERATE OF 'KINCRAIG NECK,' SHOWING RADIATING COLUMNAR STRUCTURE. EAST SIDE OF KINCRAIG POINT, ELIE, FIFESHIRE.

A prominent feature of the Scottish Lower Carboniferous is the great development of lavas and volcanic tuffs (see p. 380).

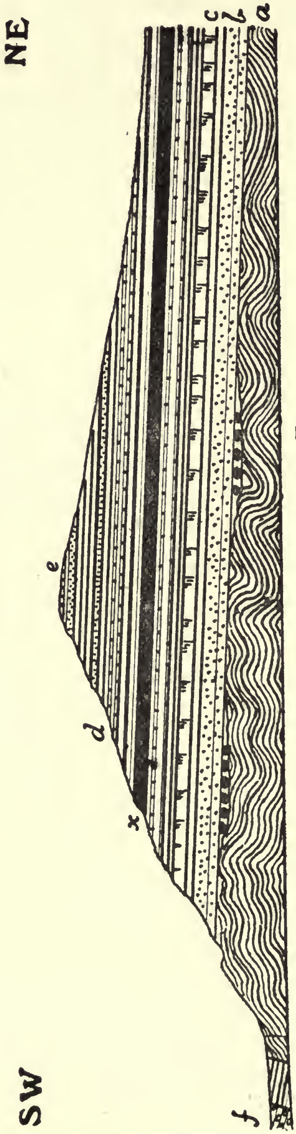


Fig. 114.—Section of Cross Fell.

a, Silurian and Ordovician; *b*, Flags and Sandstones, Quartz conglomerates, Basement conglomerates, the last in hollows in the floor of older rock; *c*, Melmerby Scar Limestone; *d*, Yoredale Series (shales, sandstones, limestones); *e*, Millstone Grit (Upper Carboniferous); *f*, Trias; *x*, Whin Sill (intrusive).

Ireland.—In Ireland the Lower Carboniferous extends with but little interruption of continuity from the southern coast to the shores of Lough Foyle, and it shows a parallel and similar variation to that which obtains in Great Britain.

In the south-west of Cork it consists of shales with interbedded calcareous bands, containing *Posidonomya Becheri*, and closely resembling the Lower Culm of Devonshire. At the base is a series of grits, the Coomhola grits. They contain *Cucullæa* and *Ptychopteria damnoniensis*, forms which occur in the Baggy beds of North Devon; but the majority of the species appear to be Carboniferous.

About the latitude of Cork massive limestones begin to appear, and towards Clare and Galway the series becomes a great limestone formation some 3,000 feet thick, with shales at the base, and occasional bands of chert.

In County Clare the Cleistopora zone is represented only by a few feet of sandy shales at the base, but the other four zones are fully developed. The Cyathaxonia subzone is recognised, though *Cyathaxonia* itself has not been found, and it is followed by black shales with a Pendleside fauna.

In County Dublin the Lower Carboniferous includes a very considerable thickness of slates and conglomerates, as well as limestones. All the zones appear to be present, though the Cleistopora zone has not been actually identified except at one or two localities. The Cyathaxonia subzone, which is well represented, is followed, as in Derbyshire and elsewhere, by beds containing *Posidonomya* and other fossils of the Pendleside series; but at Loughshinny the intercalations of Cyathaxonia beds extend upwards into the latter series to a considerably higher horizon than is usually the case.

In the north of Ireland the deposits are similar to those of Northumberland and the south of Scotland. There is a lower series of sandstones and shales with cement-stones, and an upper series of sandstones and calcareous shales with seams of coal and a few bands of compact limestone.

B.—UPPER CARBONIFEROUS

Owing to the folding and denudation which have taken place since the Carboniferous rocks were laid down, the Upper Carboniferous now forms a number of separate basins, several of which are wholly or in part concealed by newer deposits. For convenience of description these basins may be grouped as follows :—

1. The Devon syncline.
2. The Hercynian group (including the South Wales, Somerset and Gloucestershire coal-fields and the concealed coal-field of Dover).
3. The Midland group.
4. The Northern group.
5. The Scottish group.
6. The Irish group.

Throughout the British Isles the Upper Carboniferous consists chiefly of sandstones and shales, with seams of coal. The deposits are generally of fresh-water or terrestrial origin, but occasional marine bands occur at several horizons.

Towards the base of the series sandy or gritty material usually predominates, and in some districts it forms a well-defined and massive sandstone, which goes by the name of the Millstone Grit. The succeeding beds are known as the Coal Measures, and are usually divided into a Lower, Middle and Upper series. In other areas, however, the basal sandstone is broken up by intercalated beds of shale, with occasional thin seams of coal, and cannot be distinguished lithologically from the Lower Coal Measures; nor is there any difference in the contained fossils. But the name is still retained, and in most of the coal-fields the Upper Carboniferous is divided into four series:—

Upper Coal Measures.
Middle Coal Measures.
Lower Coal Measures.
Millstone Grit.

There is, however, now no doubt that the old lines of division adopted in the various coal-fields do not always correspond. Thus the so-called Upper Coal Measures of the Durham coal-field probably represent a part of the Middle Coal Measures of Staffordshire; and the Millstone Grit of the Midlands does not correspond with the Millstone Grit of Bristol. The task of drawing the boundary between the Lower and Upper Carboniferous is still unfinished, and there are still differences of opinion as to the most suitable horizon to adopt.

The difficulty arises from the nature of the deposits. In a broad and general way it may be said that the Lower Carboniferous is marine in origin, the Upper Carboniferous fresh-water or terrestrial. Quite apart from any question of age, therefore, the fossils of the two series would necessarily be entirely different. But fresh-water conditions began much earlier in the north than in the south, and the corresponding fauna appears at a lower horizon. The occasional occurrence of marine bands in the fresh-water deposits, and of plant remains amongst the marine beds, helps to remove the difficulties; but even now the correlation of the rocks in the different basins is very imperfectly known.

Fauna and Flora.—Plants and fresh-water lamellibranchs are the principal fossils found in the Upper Carboniferous. The lower part of the series is often marine, and occasional marine bands occur at higher horizons. In these there is an entirely distinct fauna, consisting chiefly of cephalopods and marine lamellibranchs.

The true systematic position of many of the plants is still uncertain. The generic names which are in common use were in most cases founded upon the stems, leaves and other vegetative organs; and there is now no doubt that plants which are in no way related have often been included in the same genus.

The Lycopodiales and Equisetales were the trees of the Coal Measure forests. But the most widely known of all the plants are the fern-like fronds which are so common in the shaly beds. Until quite recently the ferns were looked upon as the dominant class, including about half the total number of species known from the Carboniferous rocks. But the researches of the last few years tend to show that the majority of these fern-like plants bore seeds. They are now associated together as a group, called the Pteridospermeæ, which is in some respects intermediate between the ferns and the gymnosperms. True ferns appear to have been comparatively rare. Undoubted gymnosperms are also found.

The Lycopodiales are in some respects the most important group. They supplied a large part of the material from which our coal-seams have been derived; and their spores alone frequently form bands more than half an inch in thickness. *Lepidodendron* and *Sigillaria* are the principal genera, and both grew into trees of great size, sometimes attaining a height of over 100 feet. *Stigmaria* is the name applied to the roots of these and probably of other genera of Lycopods.

Of the Equisetales the most important genus is *Calamites*. Casts of the medullary cavity of the stem are very common, but the wood is usually carbonised and reduced to a mere skin of coal. *Asterophyllites* seems to represent the leaf-bearing branches of *Calamites*. *Annularia* appears to be a distinct genus. The fructification of the Equisetales took the form of cones, but they are seldom found attached.

The remarkable genus *Sphenophyllum*, which was formerly placed in the Equisetales, differs so much in its solid axis and the structure of its cone that it is now considered to constitute a distinct and unique group which soon became extinct.

The fern-like forms have been divided into a number of artificial genera based on the shape of the fronds and pinnules, the arrangement of the nerves and other external characters. The commonest of these genera are *Sphenopteris*, *Neuropteris*, *Pecopteris* and *Alethopteris*. Without the fructification, however, it is not possible to distinguish between the Ferns and the Pteridosperms. Some of the species of *Pecopteris* and *Sphenopteris* appear to have borne sporangia and may be referred to the true Ferns. But other species of the same genera, and most of the forms of *Neuropteris* and *Alethopteris*, bore seeds and belong to the Pteridosperms.

Of the undoubted Gymnosperms, *Cordaites* is the most important genus; but remains of Coniferæ, and probably of the Gingkoaceæ, also occur. Gymnospermous seeds are often found, but it is seldom possible to refer them to their parent stems. *Trigonocarpus* is one of the commonest forms.

By far the most abundant animal remains in the Upper Carboniferous are the shells of lamellibranchs. Sometimes they occur in such number as almost to constitute beds by themselves. From their affinities, and from the fact that they are always found apart from the undoubted marine forms, it is concluded that they lived in fresh water. The principal genera are *Carbonicola, Naiadites* and *Anthracomya. Carbonicola acuta* and *C. aquilina* are common forms in the Lower and Middle Coal Measures. *C. robusta, C. turgida* and *Naiadites quadrata* are abundant in the Middle Coal Measures, but rare in the lower division. *Anthracomya phillipsi* is the commonest form in the Upper Coal Measures.

Besides these lamellibranchs, remains of fish are also abundant, and several genera of amphibians have been found. Insects, spiders, &c., also occur; and in some beds Entomostraca are found in swarms.

All these forms occur in the normal deposits which constitute the greater part of the series. But at various horizons throughout the series there are bands of rock which contain a totally distinct fauna, and one which evidently lived in the sea. Cephalopods and lamellibranchs are the commonest forms, but gastropods and brachiopods also occur in considerable numbers. The cephalopods are mostly goniatites (in the wider sense of the term), and include *Gastrioceras carbonarium, G. listeri, Glyphioceras spirale.* Amongst the lamellibranchs are *Nucula oblonga, Nuculana acuta* and *Pterinopecten papyraceus.*

Classification of the Upper Carboniferous.—As the subdivision of the Upper Carboniferous must ultimately depend principally upon the distribution of the plants, a brief summary is given here of the classification proposed by Mr. Kidston. According to him, the Upper Carboniferous may be divided into four series, as follows:—

4. Upper Coal Measures.
3. Transition Series.
2. Middle Coal Measures.
1. Lower Coal Measures and Millstone Grit.

Plants are rare in the Millstone Grit, or too imperfectly preserved to admit of satisfactory identification; but all the species which have been found occur also in the Lower Coal Measures, and palæontologically, therefore, the Millstone Grit and the Lower Coal Measures must be considered as a single series.

In the Lower Coal Measures the commonest plants are *Neuropteris heterophylla, Alethopteris lonchitica, A. decurrens, Sphenopteris obtusiloba, Lepidodendron ophiurus, Calamites Suckowii* and *C. ramosus. Sigillaria* is not very common, although several species are found. All the forms mentioned occur also in the Middle Coal Measures, but they are there associated with others which are unknown in the lower division. Several species of plants are found only in the Lower Coal Measures, but they are all more or less rare, and the division is characterised not, so much by the presence of these as by the absence of many forms which are common in the Middle Coal Measures.

In the Middle Coal Measures the genus *Sphenopteris* attains its greatest development. The species *S. grandifrons*, *S. Marratii* and many others are characteristic. *Neuropteris* is also represented by a greater number of species than in the Lower or Upper Coal Measures. *Calamites* and *Sphenophyllum* are very abundant, but most of the species are found also at other horizons. *Lepidodendron* is about as abundant as in the Lower Coal Measures, and *L. ophiurus* is still the commonest form. *Sigillaria*, however, has multiplied greatly, and here reaches its maximum. *Sigillaria polyploca*, *S. elongata*, &c., appear to be peculiar to this division.

The Transition series is characterised, not by any special forms, but by containing a mixture of Middle and Upper Coal Measure plants in nearly equal proportions.

The Upper Coal Measures are characterised especially by the abundance of *Pecopteris*, the species *P. arborescens*, *P. cyathea* and many others being peculiar to this division. Another very common fern is *Alethopteris Serli*, which is found also, but rarely, in the Middle Coal Measures. *Neuropteris flexuosa* is also common. *Calamites* and *Lepidodendra* are becoming rare, and only one species of *Sigillaria*—*S. tesselata*—is at all common.

Local Variations in the Upper Carboniferous

The Devon Area.—The Upper Carboniferous occupies the greater part of the syncline which lies between the Devonian rocks of the north and south of the county. It consists of alternations of shale and fine-grained sandstone, sometimes in thin bands, sometimes in thicker and more massive beds. In the north of Devon there are inconstant bands of impure coal or 'culm,' but they are not found on the southern side of the synclinal. Occasional beds of impure limestone are also present, and bands of calcareous nodules are by no means rare.

The limestone beds sometimes contain goniatites, sometimes plants. The calcareous nodules commonly contain a marine fauna, especially *Gastrioceras carbonarium*, *Pterinopecten papyraceus*, fish-spines,—forms which are found in the Coal Measures of the Midlands and the North. The shales and sandstones yield remains of plants and freshwater shells such as *Carbonicola acuta*. The plants indicate a Middle Coal

Measure age. No trace of the Upper Coal Measures has been found, and the presence of the Lower Coal Measures has not been proved.

The Hercynian Group.—Through the Mendip Hills and the southern promontories of Wales there runs a zone of intense folding, which may be traced westwards into the south of Ireland and eastwards into Belgium and beyond. The trend of the folds is approximately from west to east, and they were produced at the close of the Carboniferous period. They form the outer zone of a great system of mountains which at that time was raised across the middle of Europe, but of which only fragments now appear from beneath the later deposits. It is the Hercynian system of Bertrand, and was the most prominent feature in the geography of Europe at the close of the Palæozoic era.

Immediately to the north of the Hercynian range, and in part involved within its folds, lies a series of coal-fields. In Ireland there are the Munster and Leinster coal-fields; in Britain, the coal-fields of South Wales, the Forest of Dean, Bristol and the neighbourhood, and also the hidden coal-field of Dover; in Belgium and the north of France, a long and narrow band, the greater part of which lies buried beneath the later beds; in Germany, the coal-field of the Ruhr.

The edge of the folded zone is often thrust over the coal-basin in front of it; and in the process the southern rim of the basin has been so extraordinarily crumpled that a vertical shaft may pass through the same coal-seam five times in succession. This is very clearly seen in Belgium, where the folded Devonian and Lower Carboniferous rocks of the Ardennes have been pushed over the coal-field of Liège. In England the Mendip Hills correspond with the massif of the Ardennes, and as the Mendips are approached from the north, the same crumpling and overfolding of the coal-seams is observed, and the Carboniferous Limestone masses of Vobster and Luckington appear to have been thrust over the Radstock coal-field.

In the South Wales coal-field the Millstone Grit ends with a massive sandstone called the Farewell Rock, and the Coal Measures are divided into an upper and a lower productive series, separated by an intervening series of sandstones in which coal-seams are less numerous. The beds may therefore be grouped as follows:—

Upper series, with coal-seams.
Middle or Pennant Sandstone series (with workable seams west of the Taff).
Lower series, with coal-seams.
Millstone Grit.

In South Wales the coals, which are bituminous in the east, gradually lose their volatile constituents towards the west, and are converted into anthracite. This is true especially of the lower division. and it is accordingly this division which yields most of the steam-coal for which South Wales is famous.

In the Bristol coal-field the Millstone Grit belongs, in part at least, to the Lower Carboniferous; in the Forest of Dean it begins in the Seminula zone. In both areas there is an arenaceous development in the midst of the Coal Measures, but not at the same horizon.

As shown by the plants, the Coal Measures of the Forest of Dean belong entirely to the Upper Coal Measures; in the Bristol coal-field they include also the Transition series; while in South Wales they extend from the Middle to the Upper Coal Measures. The Lower Coal Measures are unrepresented, and it appears that in this area there must be an unconformity, with overlap, at the base of the series.

The coal-seams which have been revealed by the borings near Dover clearly belong to the same series of coal-basins, and must lie immediately to the north of the folded zone. The structure is not yet known; but the plants which have been found show that the beds belong to the Transition and Middle Coal Measures.

Midland Group.—The Midland group includes the coal-fields of Lancashire, North Staffordshire, Yorkshire, and Nottinghamshire, Leicestershire, Warwickshire, South Staffordshire, and the strips of Carboniferous rock which rest against the eastern flanks of the Cambrian massif in the Welsh borderland.

They are separated from the northern coal-fields by a broad anticline, which runs from Morecambe Bay to Richmond in Yorkshire, approximately from west to east. Another anticline which runs from south to north in Derbyshire and West Yorkshire, divides the coal-fields of Lancashire and North Staffordshire from that of Yorkshire and Nottinghamshire.

Over a large part of the Midland area the Carboniferous rocks are concealed by newer beds, and several of the exposed coal-fields must be continuous with one another beneath the surface.

One of the characteristic features of the Upper Carboniferous of this region is the development of a series of red marls and sandstones towards the top. These were formerly referred in part to the Permian, but they contain plants and lamellibranchs belonging to the Upper Coal Measures.

At the base is the Pendleside series consisting of black shales and limestones with a marine fauna, including *Posidonomya becheri*, *Pterinopecten papyraceus*, *Glyphioceras spirale*, &c. This series is followed by a thick mass of sandstone and shales, called the Millstone Grit. As the Millstone Grit in many areas forms the base of the Upper Carboniferous, the Pendleside beds were formerly referred to the Lower Carboniferous, and were believed to be the equivalents of the Yoredale series of the northern Pennines. Wheelton Hind and Howe showed that the fauna is distinct, and is much more closely connected with that which occurs in the marine bands of the Millstone Grit and Lower Coal Measures. But the discovery of Pendleside forms in the Yoredale beds has again suggested that the two series may be at least in part contemporaneous.

In some of the coal-fields of the Midland group there is an unconformity between the red beds and the coal-bearing series below; in others no break has been detected.

The succession in North Staffordshire may be taken as typical of the Midland region, and may be summarised as follows:—

4. Red and Grey Series	Keele Series .	Red and purple sandstones and marls, with thin seams of coal and thin bands of limestone.
	Newcastle Series .	Grey sandstones and shales, with four thin seams of coal. Entomostracan limestone at base.
	Etruria Marl .	Mottled red and purple marls and clays; with thin bands of green grit.
	Black-Band Series.	Grey sandstones, marls and clays, with numerous thin seams of coal and Black-Band ironstone.
3. Grey or Chief Coal-bearing Series.	Alternations of sandstone, shale, fire-clay, seams of coal and ironstone. Marine beds occur at intervals.	
2. Millstone Grit.		
1. Pendleside Series (? Lower Carboniferous).		

Occasional red beds occur in the Grey series. In the upper series one or two bands of limestone with *Spirorbis* have long been known, and have been considered characteristic of the Upper Coal Measures. But at least one similar band has been found in the Grey series.

According to Kidston, the Grey series represents the Lower and Middle Coal Measures. The Red and Grey series belongs for the most part to the Upper Coal Measures.

Northern Group.—This group includes the Northumbrian coal-field on the east of the Pennine Chain and the Cumberland coal-field on the west. Besides the main basins there are several small outliers, which owe their preservation to faulting.

The Upper Carboniferous is divided, as it is elsewhere, into the Millstone Grit and the Lower, Middle and Upper Coal Measures. The Millstone Grit is not very clearly defined. In Cumberland the top beds of the Coal Measures consist of reddish sandstone and shales, with a band of *Spirorbis* limestone. They are believed to rest unconformably upon the productive series, and no doubt represent the Upper Coal Measures or Red and Grey series of the Midlands. In the Northumbrian coal-field, however, no representative of the true Upper Coal Measures is known.

Scotland.—In Scotland the Upper Carboniferous occupies several basins in the Central Lowlands. The largest areas are those of Ayrshire in the west, Stirling and Lanark in the middle, and Fifeshire and Midlothian in the east. A small outlying patch at Canonbie, in Dumfriesshire, which lies upon the margin of the Southern Uplands, should be grouped with the north of England coal-fields, rather than with the Scottish Lowland basins.

The succession is in general as follows :—

Red sandstones, marls, fire-clays and shales, with thin beds of impure coal.
White and grey sandstones, dark shales, fire-clays, ironstones and coals.
Roslin Sandstone or Moorstone Rock.

The Roslin Sandstone is correlated with the Millstone Grit of England. The Grey series, with productive coal-seams, belongs to the Lower Coal Measures. The Red series, in spite of its lithological resemblance to the Upper Coal Measures of the English Midlands, contains Middle Coal Measure plants, and must be referred to that series. The true Upper Coal Measures are absent, except perhaps in the Canonbie coal-field.

Ireland.—Upper Carboniferous rocks occur both in the north and the south of Ireland.

In the south there is a large area in Clare, Limerick and Kerry, a smaller but commercially more important basin north of Kilkenny, and several still smaller patches. In all, the succession is not unlike that of the Midland coal-fields of England, excepting that the Upper Coal Measures are absent ; and the beds may be grouped as follows :—

'Middle Coal Measures,' with productive seams of coal.
'Lower Coal Measures,' with thin coal-seams and some marine bands.
Flagstone group, consisting of flagstones and shales.
Black shale group, with *Pterinopecten papyraceus*, *Posidonomya becheri*, &c.

The Black shale group is clearly the equivalent of the Pendleside series. The Flagstone group no doubt represents the Millstone Grit of the Midlands. The precise correlation of the coal-bearing series has not yet been determined.

In the north of Ireland there are several basins, the largest being that of County Leitrim. The succession is nearly the same as in the south ; but denudation has removed the greater part of the productive Coal Measures.

C.—VOLCANIC ROCKS

During the earlier part of the Carboniferous period the normal progress of sedimentation was interrupted in some districts by extensive volcanic eruptions, some of which originated beneath the sea and others upon the land. It was in Scotland that these manifestations attained their maximum development, but eruptions on a smaller scale took place in Derbyshire and the Isle of Man, in Somerset and Devonshire, and in the south of Ireland. It is an interesting fact that the great centres of volcanic activity lay in the same area as those of the old Red Sandstone, although a long period of quiescence must have intervened between the two series of eruptions.

Scotland.—The Carboniferous volcanic rocks of Scotland occur chiefly in the Central Lowlands, but they extend southwards into Berwickshire and Roxburghshire, and even for a short distance across the border. The eruptions began at the end of the Old Red Sandstone period and ceased immediately before the deposition of the Coal Measures.

Two types or phases are recognised by Sir Archibald Geikie—the Plateau phase and the Puy phase. The Plateau phase was marked by the eruption of streams of lava, which spread over wide areas and formed lava-fields of great extent and thickness. The Puy phase was characterised by the discharge of fragmental material, which accumulated in innumerable scattered cones like the Puys of the Auvergne. The Plateau phase was the earlier, though the two may have overlapped to a certain extent.

The Plateau phase was, on the whole, remarkably free from explosive outbursts. Fragmental material forms only a small proportion of the discharges. The lavas appear to have welled up quietly, but so widely did they spread and so frequently were they poured out that the fields of lava sometimes exceeded 2,000 square miles in area and 3,000 feet in thickness. In the east the eruptions began at the close of the Old Red Sandstone period; in the west they did not commence until a considerable thickness of Carboniferous rocks had been deposited. Everywhere the Plateau type ceased before the commencement of the Scottish 'Carboniferous Limestone series.'

The principal plateaux of which the remains are still preserved are—

1. The Clyde plateau, which extends from Stirling to the Clyde, and on the western side of the Clyde covers a wide area in Renfrewshire, Lanarkshire and Ayrshire, and spreads over into Arran and the Mull of Cantyre.
2. The Garleton plateau, forming the Garleton Hills in East Lothian.

3. The Midlothian plateau, the fragments of which extend from Arthur's Seat in Edinburgh south-westwards nearly to the Clyde.
4. The Berwickshire plateau, in the valley of the Tweed, near Kelso.
5. The Solway plateau, of which the edge is seen in Dumfries and Kirkcudbright.

As has already been remarked, these plateaux are formed chiefly of lavas, but sometimes they include thin bands of tuff, and in a few localities the fragmental material attains a considerable thickness, and may even form a large proportion of the whole volcanic series. Most of the lava-flows are andesitic, but more basic and more acid rocks are sometimes met with. Ultrabasic lavas occur occasionally, especially towards the base of the series. In the Garleton Hills the andesites and basalts are overlaid by sanidine trachytes. The phonolite of Traprain Law forms a plug in the Garleton plateau.

The Puy phase seems to indicate the gradual decay of the volcanic forces. The products of eruption no longer formed widespreading fields of lava, but accumulated in scattered cones, many of which were very small, both in height and width. Most of the Puys consist of fragmental material alone, but from some of the larger cones were poured out streams of lava of considerable extent. The Puy phase followed the Plateau phase, but it is probable that the change from the one to the other did not take place at the same time throughout the area. On the whole, the Plateau lavas belong to the Calciferous Sandstone series, the Puys to the Carboniferous Limestone series; but in some districts the Puy eruptions began during the deposition of the Calciferous Sandstone. It was in Ayrshire that the eruptions continued longest, but even here they ceased before the Coal Measures began to be formed.

The volcanic rocks of the Puy phase are generally basic. Most of the lavas are basalts. They may be either with or without olivine, but the olivine-bearing basalts predominate. The tuffs, like the lavas, are generally basic in composition.

North of England.—The contemporaneous volcanic rocks of the Scottish area extend only a very short distance across the border. But in the north of England many dykes and sills are intruded into the Carboniferous beds. Some of these certainly belong to a much later period. The Cleveland dyke, for example, cuts through the Carboniferous, Permian, Triassic and Jurassic rocks, and was probably intruded during the Tertiary era. But others may be of older date.

The greatest of these intrusions is the Whin Sill, a sheet which extends with little interruption from the Farne Islands in Northumberland to Burton Fell in the Pennine Chain. It is a dolerite which in its coarser central portion approaches a gabbro in appearance. It contains no olivine, but bronzite occurs in small quantities. There is no evidence as to its age excepting that it is later than the Lower Carboniferous rocks into which it is intruded. But Sir Archibald Geikie is inclined to associate it with the eruptions of the Carboniferous period.

Derbyshire.—In the Carboniferous Limestone of Derbyshire there are several bands of igneous rock, which are locally known as toadstone. Some of these are undoubtedly contemporaneous lavas and tuffs, but others are probably intrusive sills. In composition they are mostly olivine basalts and olivine dolerites.

Isle of Man.—Bedded volcanic tuffs are interstratified with the Lower Carboniferous rocks of the south end of the Isle of Man. Necks of agglomerate and intrusive dykes and sills also occur, but no lavas have been observed.

South-west of England.—Igneous rocks occur in the Lower Carboniferous of North Somerset and the south of Devonshire. Some of these are probably intrusive, but others are contemporaneous. Brent Tor, near Tavistock, is believed to be the site of a Carboniferous volcano.

Ireland.—Although the greater part of Ireland is covered by Lower Carboniferous beds, no sign of volcanic activity has been observed except in Limerick, and possibly in King's County and County Cork.

Near Limerick the Carboniferous Limestone forms an oval basin about twelve miles long, with an outer and an inner rim of volcanic rocks. The two volcanic series are separated by one or two thousand feet of sedimentary material. The lower series is formed partly of tuffs and partly of lavas. Some of the lavas are andesitic and resemble those of the Plateau phase of Scotland, but basalt also occurs and apparently in larger quantity. The lavas of the upper series are mostly basalts.

Volcanic breccias are found in King's County north of Philipstown and also in the south-west of County Cork. Probably they belong to the Carboniferous period, but their age has not been satisfactorily determined.

CHAPTER XXIII

THE PERMIAN SYSTEM

The close of the Carboniferous period was characterised, not only in England but also over a large part of Europe, by extensive movements of the earth's crust. The most violent crumpling took place along a broad zone which stretched from west to east, and resulted in the elevation of the great Hercynian mountain system already described. But the movements were not confined to the zone of crumpling. Outside the Hercynian range the Carboniferous beds were thrown into broad anticlines and synclines, sometimes accompanied by faults of great magnitude. It is to these that the separation of the British coal-basins is chiefly due.

The folding took place before the Permian beds were laid down; and not only were the folds completed, but they were also denuded to so great an extent that the Lower Carboniferous rocks were exposed. Upon the irregular floor which was thus produced the Permian strata were deposited, and they rest unconformably upon the Coal Measures, the Millstone Grit, the Lower Carboniferous and sometimes on still older rocks.

Between the deposition of the Coal Measures and the Permian (Fig. 115) there must, therefore, have been a considerable interval of time, during which the greater part of Northern Europe was land. But the south and east of Europe and Central Asia were covered by the sea, for in those regions there is a continuous succession of marine deposits from the Carboniferous to the Permian.

The conditions were somewhat similar to those which prevailed during the Devonian period. There was a continent in the north and west of Europe, while the sea spread over the south and east. But the land extended farther to the south than in Devonian times.

The Permian deposits of Northern Europe were laid down upon the continent, partly upon the surface of the land itself, partly in landlocked seas which resembled the present Caspian and Sea of Aral. In these seas dwelt an impoverished fauna which was originally derived from the waters of the Carboniferous ocean.

Fauna.—The conditions which prevailed in North-western Europe were thus unfavourable to life. The majority of the Carboniferous

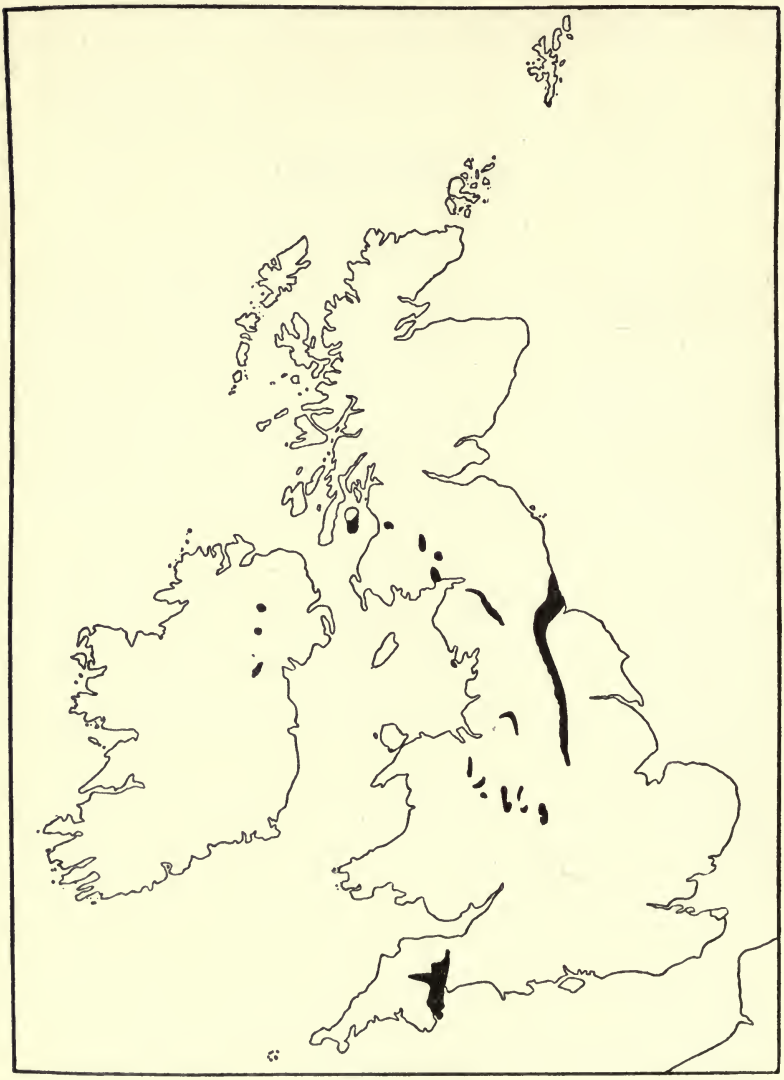


FIG. 115.—THE PERMIAN SYSTEM.

genera became extinct, without leaving any descendants; and those which still survived were represented generally by small and sometimes abnormal forms, which seem to have lived in an unsuitable environment. Nor was there any considerable introduction of new types. The fauna is such as might be expected if arms of the Carboniferous sea had been cut off from the open ocean and had gradually become too salt for the majority of their inhabitants. The number of species is therefore small; but a few appear to have thriven under the new conditions, and the individuals are occasionally very numerous. This is especially the case with the Polyzoa, which sometimes form masses of considerable thickness.

Of the groups which were so prominent in the Carboniferous seas, the corals, echinoderms and cephalopods had almost disappeared. No trilobites are known in the British Permian, but one or two species have been found abroad. Several of the genera of brachiopods, lamellibranchs and gastropods still lived on, though generally in diminished numbers. The brachiopods *Productus horridus* and *Spirifer alatus*, and the lamellibranchs *Schizodus Schlotheimi* and *S. obscurus*, are amongst the best-known forms; and gastropods, such as *Turbo* (*Polytropis*) *helicinus*, are sometimes very abundant.

Polyzoa, as already remarked, sometimes form the greater part of the limestone bands. *Fenestella retiformis* is a characteristic species.

Fish are relatively abundant, and are represented by many genera, such as *Platysomus* and *Palæoniscus*.

Footprints of Labyrinthodonts are not uncommon, and their bones have been found abundantly in the Permian of Germany. In Germany also the earliest-known remains of reptiles (*Proterosaurus* and *Palæohatteria*) are found in the Permian deposits.

Plants are not usually abundant in the English Permian, and many of the species are survivors from the Coal Measure period. The most characteristic forms are *Odontopteris obtusiloba, Callipteris conferta, Calamites gigas* and *Walchia piniformis*.

While the isolated survivors of the Carboniferous fauna were dying in the landlocked seas of Northern Europe, in the open ocean of the south the normal process of development went on. New forms were there evolved to replace the older types, and in particular the ammonites so characteristic of the Mesozoic era began to appear. There is here no break between the Carboniferous and the Permian, nor, perhaps, between the Permian and the Trias.

The Permian beds crop out in a long strip which extends from Nottingham to the coast of Durham. They occur also on the west of the Pennine Chain in Lancashire, Westmorland and Cumberland, especially in the Vale of Eden. Certain deposits in the Midlands and in Devonshire are usually referred to this system. A few small patches of red sandstone with interbedded lavas in Scotland may belong either to the Permian or the Trias. Undoubted Permian rocks occur in Ireland, but only to a very limited extent.

East of the Pennine Chain

In the north-east of England the prominent member of the Permian system is the Magnesian Limestone. It is admirably displayed in the cliffs of the Durham coast, and also forms a well-defined escarpment overlooking the coal-field on the west. It is a variable deposit, sometimes cavernous, with numerous hollows lined with crystals, sometimes compact and crystalline in texture, sometimes made up almost entirely of globular concretions. Usually it consists chiefly of carbonate of lime and carbonate of magnesia in nearly equal proportions, but sometimes it becomes highly siliceous. Thus the well-known red and white sandstones of Mansfield, in Nottinghamshire, contain over 50 per cent. of silica, but in a very short distance they seem to pass laterally into a yellow dolomitic limestone.

In Durham the Magnesian Limestone is preceded and followed by marls and sands, generally of inconsiderable thickness, and the Permian succession is—

4. Red Marls and Sandstones.
3. Magnesian Limestone.
2. Marl Slate.
1. Yellow Sands.

The sands at the base are generally soft and friable. They fill up the hollows of the uneven floor on which the Permian was deposited, and accordingly they vary greatly in thickness and are often absent altogether.

The Marl Slate is a calcareous shale, not more than a few feet thick. But it is remarkably persistent, and is well characterised by the abundance of fish remains which it contains.

The Magnesian Limestone of Durham is more than 600 feet in thickness. The lower part is generally compact and poor in fossils. The middle portion is often more cavernous, and is the most highly fossiliferous member of the whole system. The upper beds are often concretionary or oolitic, with few fossils.

The Red Marls and Sandstones can with difficulty be separated from the overlying Trias, and are here very thin.

In Yorkshire a band of red marls appears in the middle of the limestone, and the succession therefore becomes as follows :—

6. Upper Red Marls.
5. Upper or Brotherton Limestone.
4. Middle Marls and Sandstones.
3. Lower Limestone.
2. Marl Slate.
1. Yellow Sands.

The upper beds are sometimes overlapped by the Trias.

Towards the south the calcareous beds diminish in thickness. In Durham the Magnesian Limestone is more than 600 feet thick. In Yorkshire the upper and lower limestones together do not exceed about 450 feet; in the south of the county they are only about 200 feet. The Upper Limestone disappears near Worksop, and the Lower Limestone dies out at Nottingham.

The marls and sands, on the other hand, increase (cp. Fig. 116). Omitting the soft sands at the base, which are very capricious and local in distribution, the Marl Slate at the mouth of the Tyne is about 3 feet thick, in Yorkshire 10 to 12 feet, in Nottinghamshire the beds that are supposed

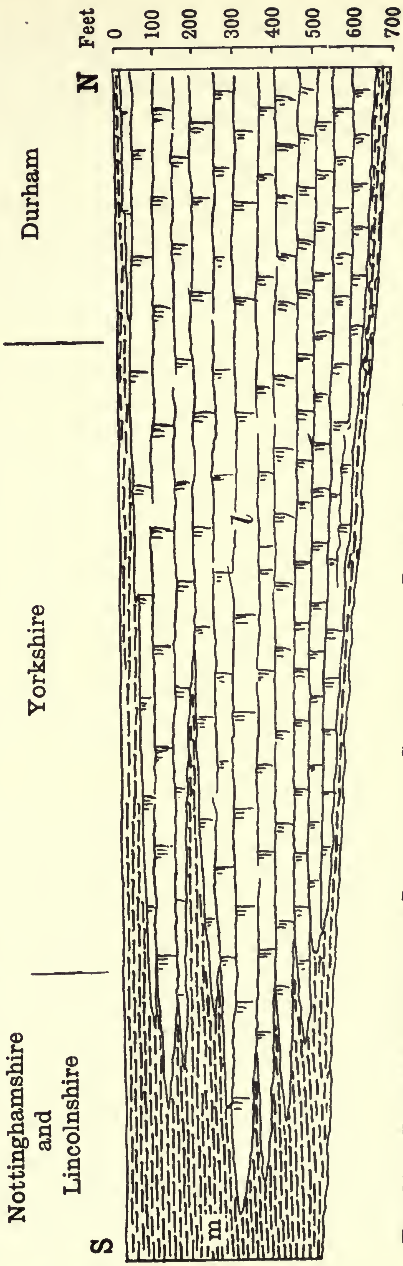


FIG. 116.—DIAGRAM SHOWING THE LITHOLOGICAL CHANGES OF THE PERMIAN ON THE EASTERN SIDE OF THE PENNINE CHAIN.

l, Magnesian Limestone; *m*, Marls and sands.

to represent it, attain a thickness of 50 to 150 feet, and at South Scarle, in Lincolnshire, of nearly 200 feet.

In Durham the Middle Marls are absent. In South Yorkshire they are from 30 to 50 feet thick, and at South Scarle about 140 feet.

The Upper Marls appear to be thin or absent in Durham. In Yorkshire they are at least 50 feet in thickness, and at South Scarle about 80 or 100 feet.

The whole system therefore becomes more marly and sandy towards the south, indicating the neighbourhood of the old shore-line. At Nottingham it is completely overlapped by the Trias; and it does not appear ever to have extended much farther.

West of the Pennine Chain

On the western side of the Pennine Chain the Permian occurs along the southern border of the Lancashire coal-field and in the Vale of Eden. There are also a few small outlying patches in the north of Lancashire.

The deposits are very different from those of the east of England. The Magnesian Limestone is no longer a conspicuous feature, and the greater part of the system consists of red sandstones, marls and breccias. In the south of Lancashire, however, the upper division is a series of marls and thin limestones with fossils similar to those of the Magnesian Limestone.

In the Valley of the Eden the beds may be grouped as follows:—

[4. Red Marls and Shales (? Trias).]
3. Magnesian Limestone.
2. Hilton Shales.
1. Red sandstones with breccias and conglomerates (Brockram).

The red arenaceous series at the bottom forms by far the greater part of the system, and in some places attains a thickness of 1,500 feet. Towards the north it consists almost entirely of a current-bedded red sandstone, called the Penrith sandstone; but towards the south it includes beds of coarse conglomerate or breccia, locally known as Brockram. The fragments or boulders in the brockram beds consist chiefly of Carboniferous Limestone; the matrix is sandy and fine in texture. Some writers have supposed them to be of glacial origin; but they are now more usually looked upon as screes. They thicken greatly towards the southern end of the valley.

The Hilton Shales are dark-coloured shales containing numerous remains of plants. The remains are generally too fragmentary for identification, but they include *Alethopteris*, *Sphenopteris*, *Ulmannia*, &c.

The Magnesian Limestone is only a narrow band, not exceeding 25 feet in thickness.

The red shales and marls, which generally lie upon the Magnesian Limestone, were formerly included in the Permian; but as they sometimes rest upon the other members of the system, they appear to be unconformable and accordingly are now placed in the Trias.

The Midlands

Upon the margins of many of the Midland coal-fields a series of marls, sandstones, conglomerates and breccias has long been referred to the Permian system. Recent researches have shown that some of the beds, such as the Keele series of the North Staffordshire coal-field, really belong to the Coal Measures; and it has even been doubted whether any of the deposits are of Permian age. The conglomerates, however, include pebbles of Carboniferous sandstone, indicating a considerable interval of denudation, and the Trias seems to rest upon them unconformably. In Leicestershire they are separated by unconformities both from the underlying Coal Measures and the overlying Trias. In the absence of palæontological evidence, therefore, these beds must still be referred to the Permian.

In South-east Shropshire and in South Staffordshire two groups may be recognised—

2. An upper group of marls with 'trappoid breccias,' the breccias being especially developed towards the base.
1. A lower group of calcareous sandstones, locally conglomeratic, interbedded with marls and sandstones.

The pebbles of the lower group have been derived chiefly from the pre-Permian limestones, especially the Carboniferous, Wenlock, and Woolhope Limestones. The breccias of the upper group are formed mostly of fragments of Archæan lavas and tuffs, with, in certain localities, many pieces of Llandovery sandstone.

In both cases, no doubt, the source of the fragments was the old ridge which has already been shown to have stretched across the middle of England in Carboniferous times. During the denudation of this ridge the newest, and therefore uppermost, rocks would first be worn away; and not till the later rocks had been removed would the Archæan core be exposed.

The fragments of the Permian breccias are occasionally striated, and they were held by Ramsay to be glaciated boulders. But the striations seem really to be of the same nature as slickensides. They are most marked where the beds have been most disturbed, and they are found not only on the fragments themselves, but also on the matrix in which the fragments are imbedded.

Devonshire

A somewhat similar series of sandstones, breccias and marls rests against the eastern flank of the Devonshire plateau, and is followed by the Trias. A narrow tongue extends past Crediton into the middle of the Carboniferous syncline.

No fossils have been found in these beds. They rest unconformably upon the Culm and must be post-Carboniferous; but there is no decided break between them and the overlying Trias. It is possible, therefore, that they may belong to that system. But they closely resemble the Permian breccias and conglomerates which wrap round so many of the ancient 'horsts' of Northern Europe.

The Devonshire breccias were evidently in part derived from the old rocks against which they rest. Pieces of Devonian limestone are abundant in the lower beds. But in the higher breccias, as in the upper or 'trappoid breccias' of the Midlands, fragments of old volcanic rocks are present.

Intercalated amongst these sedimentary deposits are several sheets of lava, which are evidently of contemporaneous origin.

Scotland

In Ayrshire, Dumfriesshire, on the shores of Loch Ryan in Wigtownshire, and in the isle of Arran, a series of red sandstones, breccias and conglomerates lies unconformably upon the older rocks. No fossils have been found in them, and their age is still uncertain. They have been referred sometimes to the Permian, sometimes to the Trias. In their general character they resemble the breccias of the Midlands and of Devonshire, and were evidently formed under similar conditions.

In Ayrshire the series rests unconformably upon the Coal Measures. At the base are contemporaneous lavas and tuffs, and with these are associated numerous volcanic rocks which pierce the Coal Measures. Many of the volcanic rocks of Fifeshire probably belong to the same period, and Sir Archibald Geikie believes that the latest eruptions of Arthur's Seat in Edinburgh took place about the same time.

Ireland

In the north-east of Ireland there are a few small patches of Permian rocks. Magnesian Limestone occurs in the east of County Tyrone and on the south shore of Belfast Lough. At Armagh there is a breccia and boulder-bed similar to the brockram of Cumberland.

CHAPTER XXIV

THE TRIAS, OR TRIASSIC SYSTEM

In general the English Trias (Fig. 117) lies unconformably upon the rocks below. Occasionally where it rests upon the Permian there is no sign of a break, and owing to the rarity of fossils it is sometimes impossible to determine with certainty the boundary between the two formations. But even to the Permian it is often unconformable; and in most directions it overlaps the Permian and rests directly on the older rocks. Moreover, the higher beds of the Trias overlap the lower (see Fig. 118, p. 397), spreading on almost every side beyond the limits of the latter; and thus it is clear that the deposits were laid down in basins which were partially or entirely enclosed, and which were gradually filled up.

The basins were not occupied by the sea, nor by fresh-water lakes. Excepting in the uppermost beds there are no fossils that can be classed as undoubtedly marine, and fossils of any kind are generally rare. The deposits are chiefly red and variegated sands and marls, with pebble-beds in the lower portion. False-bedding is almost universal in the sandstones, and layers of rock-salt and gypsum occur in the marls. In many places the beds of the Trias abut against prominences of the ancient floor, which rise up through them and evidently were hills or islands when the Trias was laid down. In the Mendips and in Charnwood Forest it is even possible to restore with some degree of accuracy the features of the Triassic landscape.

The Trias, then, was not laid down upon the smooth floor of an open sea, but upon the irregular surface of a continent. Gradually the deposits filled the hollows and spread over the hills, though probably the higher peaks were never completely buried. The conditions were not unlike those of the Torridonian and Old Red Sandstone periods.

But although the Trias was of continental origin, it is not clear how much of the material was deposited beneath terrestrial waters and how much on the surface of the dry land itself. The occurrence of rock-salt and gypsum clearly proves the presence of salt lakes. The well-rounded pebbles of the Lower Trias are certainly water-worn.

Sun-cracks, the marks of rain-drops and the footprints of animals show that once the marls were muds, which were quickly dried and

FIG. 117.—THE TRIASSIC SYSTEM.

buried beneath the next succeeding layer. Such markings are most likely to be preserved around the margins of lakes with gently sloping shores, where a small increase in the volume of water means a large increase in the area of the lake. Or they may have been formed on nearly level surfaces which were subject to temporary floods.

Much of the deposit, however, was probably wind-borne. Sometimes the grains of sand are very perfectly rounded; often the false-bedding is similar to that of sand-dunes. Moreover, in Charnwood Forest it has been shown that the ancient rocks against which the Trias rests have been scored and polished by wind-blown sand.

On the whole, therefore, the Trias appears to have been laid down under conditions similar to those which now prevail in the dry interior of continents. The lower-lying country between the mountain ranges was covered by wind-blown sand and alluvial deposits washed down from the hills during occasional floods, and gradually the mountain-chains were more or less completely buried. In hollows in the nearly level plains that were thus produced, the water collected and was evaporated, forming lakes of brine, and finally deposits of sodium chloride and other salts.

Similar conditions appear to have prevailed throughout North-western Europe, including Germany and France. But in Germany a band of limestone known as the Muschelkalk is intercalated in the midst of the system. In this lamellibranchs and other marine fossils are often abundant, showing that during the middle of the period the sea spread for a time over the margin of the northern land.

In the Alps and the south of Europe generally the corresponding deposits are for the most part purely marine. And thus, during the Triassic period, as in Devonian times, the continent must have lain in the north of Europe and the open ocean towards the south.

At the close of the period the sea again spread far into the northern continent. The latest stage of the Trias, known as the Rhætic, contains marine fossils at least as far north as Yorkshire and Antrim.

In the centre of England the Trias covers a large area which is roughly quadrangular in shape, and measures about forty miles from north to south and from east to west. But the covering is not complete. In some places it has been worn away so as to expose the beds beneath; elsewhere the ancient rocks which pierce it are the peaks of hills which never were completely buried.

From this central area proceed three arms or branches, one from each of the corners excepting that which looks south-east. North-west the Trias spreads over Cheshire and the south and west of Lancashire to the coast of Cumberland. North-east it stretches along the valleys of the Trent and Ouse and reaches the sea at the mouth of the Tees. South-west it extends down the valley of the Severn, and thence as a discontinuous band through Gloucestershire, Somerset and Devon to the English Channel near Sidmouth.

There are, moreover, a few outlying tracts. Triassic deposits fill the greater part of the Vale of Clwyd in North Wales, and the Vale of Eden in Cumberland. In the south of Scotland there are several small patches of red sandstone, with volcanic rocks, which may belong either to the Permian or the Trias. Undoubted Triassic rocks occur on both the western and the eastern coasts of the Scottish Highlands and also in the north-eastern part of Ireland.

Because the Trias is formed largely of soft marls and sandstones, the areas which it covers are usually low and never mountainous. But they are relieved from monotony by the conglomerates and other hard bands, which, although they never rise to any great height, often form prominent hills and steep escarpments.

Classification of the Trias.—In the English Trias three principal divisions are commonly recognised, viz.:—

3. The Rhætic.
2. The Keuper.
1. The Bunter.

The lowest division consists generally of red and variegated sandstones and pebble-beds. The second is formed of red sands and marls with layers of rock-salt and gypsum. The uppermost series is a thin but continuous band of grey and black marls with marine fossils.

In Germany the Muschelkalk, a calcareous series about 1,000 feet in thickness, is intercalated between the Bunter and the Keuper. No trace of it is found in the British Isles; but according to some authors it is represented by an unconformity. Certainly in some places the Keuper rests upon an eroded surface of the Bunter. But it is very doubtful whether there is any widespread unconformity, and it is by no means unlikely that the German Muschelkalk corresponds with a part of our Bunter or Keuper.

Fauna and Flora.—Owing to the general absence of marine deposits, the fauna of the English Trias is very limited and gives a very imperfect idea of the life of the period. Nor is the flora much more completely represented, for it is only here and there that plants are found in any abundance. The Lycopods, Equisetaceæ and the fern-like forms of the Coal Measures were not yet extinct, and a few of the Palæozoic genera still survived; but the most important groups of plants were the Conifers, e.g. *Voltzia*, and the Cycads, of which *Pterophyllum* is the commonest form.

Corals, echinoderms, brachiopods and molluscs, which are in general inhabitants of the sea, are naturally rare. A few lamellibranchs of doubtful affinities have been found in the Keuper. But it is only in the Rhætic beds that marine forms occur in any abundance. The lamellibranchs *Pteria* (*Avicula*) *contorta*, *Pecten valoniensis* and *Protocardia rhætica* are here the most important forms.

The small Crustacean *Estheria minuta* occurs in crowds upon the surface of some of the Keuper shales. It belongs to the order Branchiopoda, and its living allies dwell in terrestrial waters, either fresh or brackish or salt, but not in the open sea. Remains of scorpions have been found.

Many genera of fish are found, but seldom in abundance. The most interesting form is *Ceratodus*, the teeth of which are common in the Rhætic bone-bed. They are very similar to those of the Australian mud-fish of the present day, which is indeed referred to the same genus.

The amphibians are represented by the labyrinthodonts. Their footprints, curiously like the imprint of a human hand, are not uncommon on the fine shales of the Keuper series.

Remains of reptiles are occasionally abundant, but their distribution is singularly local. In Great Britain the most prolific locality is the neighbourhood of Elgin, where many genera have been found, including *Hyperodapedon*, *Gordonia*, *Elginia*, &c.

The earliest mammals which have yet been discovered belong to this period. The teeth of a small form named *Microlestes* occur in the English Rhætic. Two or three other genera which have been referred to the Mammalia have been found in the Trias of Germany, South Africa and the United States. Some of these, however, are doubtful, and may belong to the Reptilia.

For the marine representatives of the Trias, and consequently for the marine fauna of the period, it is necessary to go abroad. In the German Muschelkalk, marine fossils are often very abundant, but the number of species is not large. The lamellibranch *Myophoria* is one of the commonest forms. The crinoid *Encrinus liliiformis* and the cephalopod *Ceratites nodosus* are also characteristic.

It is, however, in the region of the Alps and Mediterranean that the marine facies of the Trias attains its fullest development. Here it consists very largely of massive limestones, often dolomitic, which are magnificently displayed in the Dolomites of Tirol. Some of these limestones are made up chiefly of calcareous algæ, such as *Gyroporella* and *Diplopora*, but other marine forms are also very abundant. Brachiopods no longer maintain the dominant position which they assume in so many of the Palæozoic limestones, and to a large extent their place is taken by lamellibranchs. Gastropods also are very abundant. Of the cephalopods, the nautiloid genera appear to be dying out, while the ammonoid forms are developing and have already become of considerable importance. The most characteristic of the ammonoid genera are *Ceratites* and *Trachyceras*.

The Midland District

In the Midland district the system is subdivided as follows (cp. Fig. 118):—

Rhætic series.

Keuper . . . { Keuper Marls.
Keuper Sandstone.

Bunter . . . { Upper Variegated Sandstone.
Conglomerate or Pebble-beds.
Lower Variegated Sandstone.

On the whole, the deposits become finer towards the top. The Bunter consists of conglomerates and sandstones, the Keuper of sandstones and marls, and the Rhætic chiefly of marls and shales.

The deposits are thickest towards the north-west, where the entire series is present; but towards the south and south-east the lower beds die out one after the other until in the southern part of Charnwood Forest the Keuper marls form the base of the system. The following thicknesses are given by Professors Lapworth and Watts:—

	Central Cheshire.	West and south sides of South Stafford Coal-field.	East side of South Stafford Coal-field.	East Warwick.	Charnwood Forest, &c.
	Feet.	Feet.	Feet.	Feet.	Feet.
Keuper Marls .	3000	1000	700	600	600–0
Keuper Sandstone	450	400–300	200	150	absent
Upper Variegated Sandstone.	500	300 }	300–250 {	absent	absent
Pebble-beds . .	750–500	300 }		absent	absent
Lower Variegated Sandstone . .	500–200	300–0	absent	absent	absent

Moreover, deep borings have shown that no part of the Trias extends very far beneath the later Mesozoic beds; and it is clear that in this direction the Palæozoic rocks must have formed a barrier which limited the Midland area of deposition on the south and east. As the basin to the north was gradually filled up, the higher beds spread beyond the lower and overlapped them on to the slopes of this ancient ridge.

The Keuper sandstone and the Bunter pebble-beds are harder than the rest of the formation, and their outcrops often form low lines of hills, sometimes with a steeply scarped face, which usually looks towards the north-west.

The **Lower Variegated Sandstone** of the Bunter series is usually reddish-brown in colour, but varies from yellow through brown to vermilion. It is remarkably false-bedded, but is always a sandstone and always free from pebbles.

The **Pebble-beds** of the Middle Bunter consist in general of a mass of well-rounded pebbles varying in diameter from one inch to eight or nine. The majority are yellow or brown quartzites; but pebbles of sandstone, limestone and volcanic rock occur.

The source from which these pebbles were derived is still uncertain. According to some authors, they came from the south. Others believe that they are of local origin, and others again are of opinion that they were brought from the north. During this period, as we have already seen, a ridge of high land stretched across the middle of England and might well have been the source of supply. But the greater part of the ridge is concealed beneath the later deposits, and the few peaks which are exposed are not of the material that predominates amongst the pebbles. According to Professor Bonney, the majority of the pebbles are formed of rock which can be matched in Scotland but not elsewhere in Britain; and accordingly he attributes to them a northern origin. Opposed to this view is the fact that the size of the pebbles decreases from south to north, a circumstance which seems inexplicable unless the source lay to the south. The area, however, was an intermontane basin, and there is no reason why it should not have received material from all directions.

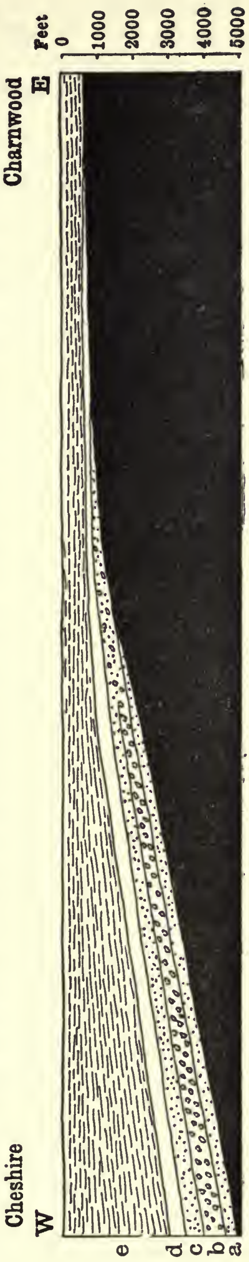


FIG. 118.—DIAGRAM SHOWING THE DIVISIONS OF THE TRIAS OVERLAPPING IN SUCCESSION ON TO THE PRE-TRIASSIC FLOOR.

***a*, Lower Bunter Sandstone; *b*, Bunter Pebble-bed; *c*, Upper Bunter Sandstone; *d*, Keuper Sandstone; *e*, Keuper Marls.**

The **Upper Variegated Sandstone** is very like the lower sandstone. It is generally fine in grain, and usually bright-red in colour, with bands and blotches of white or yellow. In some parts of the area there are occasional beds of pebbles and angular fragments.

The **Lower Keuper** is usually made of three divisions. The basement consists of coarse sandstone or calcareous breccia, with cornstones and occasional beds of marl. The middle division is a fine-grained sandstone, which often yields an excellent building-stone. The upper division consists of brownish-red laminated sandstones and sandy marls, known locally as 'water-stones,'[1] a name which is derived from the fact that they form the source of many springs, and in borings commonly give a good supply of excellent water.

The **Upper Keuper,** or Keuper Marl, covers a larger area than any of the other subdivisions. It consists chiefly of bright-red marls and shales, with occasional bands of greyish sandy and micaceous shales. Towards the Jurassic outcrop a thin grey sandstone group comes in near the top of the series, but is not invariably found. In this sandstone remains of fish (*Palæoniscus superstes*), the Crustacean *Estheria minuta* and a few lamellibranchs have been found; but the marls above and below are barren of fossils. Thin bands and seams of gypsum occur in the Upper Keuper, and it contains also, in the Worcester district, a bed of rock-salt, the brine from which has long been pumped up for the manufacture of salt at Stoke and Droitwich.

In the east of the district, in Charnwood Forest, the Keuper marls spread beyond the lower members of the system and rest directly upon an irregular and hilly surface of Archæan rocks. The Archæan outcrops of the forest are in fact only the summits of a group of hills which is for the most part buried beneath the Trias, and the valleys are filled with Keuper marl. Here there is clear evidence of wind-erosion. The surface of the old rocks is fresh and undecomposed, and is often smoothed and polished as if by wind-blown sand. The faces of the buried cliffs are fluted and undercut as in a desert region, and against them are banked the Keuper marls.

The **Rhætic beds** form a thin but continuous band between the Keuper and the base of the Jurassic system. Lithologically they resemble the latter rather than the former. They consist of dark-grey and blue marls and shales with thin bands of limestone and sandstone. They contain *Estheria minuta, Pteria contorta, Protocardia rhætica,* &c.

[1] This term is sometimes applied to the whole of the Lower Keuper.

The South-Western District

North of the Mendip Hills.—Owing to the southerly overlap, which has already been described, the prolongation of the Trias down the Severn Valley is formed superficially of the Keuper and the Rhætic only. Underground the Bunter extends for some distance, but on the surface it is absent, and it is the Keuper that rests directly against the old rocks of the Welsh borders. The overlap is still continued: the lower beds of the Keuper disappear one by one, and the base rises higher and higher in the series until in the Mendip Hills it is often the next succeeding formation, the Lias, that lies upon the older rocks. Evidently the Mendips, or at least their higher peaks, stood up through the Keuper waters or rose above the Keuper plain.

Throughout this region, therefore, the Trias consists chiefly of the Keuper marl and the Rhætic beds. The Keuper sandstone is visible at the north end of the Malvern range, but farther south it has been overlapped. Locally, however, where the formation is visible, the basement beds are often coarse conglomerates. They are made up largely of pebbles of Carboniferous limestone ranging from a few inches to two or three feet in diameter, and the matrix is usually dolomitic. Hence they are known as the Dolomitic Conglomerate. They are very local in distribution, and are evidently analogous to the very coarse gravels which are commonly deposited at the foot of a mountain-chain where the slope falls suddenly into the plain. Occasionally these conglomerates fill valley-shaped depressions worn in the older rocks. Elsewhere they occur in patches which have no regular outline.

The Keuper Marl itself differs little from that of the Midland area, and calls for no special description. Commonly the upper thirty feet or so is green in colour. These 'tea-green' marls, as they have been called, are often included in the succeeding series.

The Rhætic beds are much better exposed than in the Midlands, and the section at Penarth, near Cardiff, has long been classical. The series may be divided into two stages—

2. White Lias. Grey shales with thin bands of limestone.
1. Black Shales, with occasional bands of shelly limestone and one or two bone-beds.

The shelly limestones in the lower division contain the characteristic fossils *Pteria contorta* and *Pecten valoniensis*. The bone-beds are crowded with the teeth and fragments of bones of fish.

South of the Mendip Hills.—On the southern side of the Mendips the Trias reappears. Here again it is only the higher beds that abut against the ancient ridge; but southwards the Keuper sandstone and the Bunter come in.

Upon the eastern margin of the old rocks of Devonshire the Permian and Trias form a continuous belt of low-lying ground. Owing to the absence of palæontological evidence, it is possible that some of the beds which have been ascribed to the Permian may really belong to the Trias. But according to the grouping which is usually accepted, the Trias of this region may be divided as follows:—

Rhætic.	
Keuper . . .	Red marl with gypsum. Red and white sandstones with beds of marl; a calcareous breccia at base.
Bunter . . .	Red sandstones. Conglomerate or pebble-beds.

The succession is similar to that of the Midland counties excepting for the absence of any Lower Bunter Sandstone.

The most interesting of the deposits are the pebble-beds, which are well exposed at Budleigh Salterton. They consist of well-rounded pebbles of quartzite and grit in a red sandy matrix. Some of the pebbles contain Devonian fossils, and may have been derived from the rocks of Devonshire. Others are Ordovician grits closely resembling those of Brittany and Veryan Bay. The size of the pebbles diminishes towards the north; and it appears probable, therefore, that they have been derived from the old Armorican range of which Brittany is one of the surviving fragments.

The finer material points to a similar source. Amongst the grains are fragments of tourmaline, staurolite, fluor-spar, &c. Some of these, such as the tourmaline and fluor-spar, might readily have come from the neighbouring rocks of Devon and Cornwall, but staurolite is there unknown. Moreover, the staurolite, which forms 20 per cent. of the heavy grains near Budleigh Salterton, diminishes in quantity towards the north. From an examination of the distribution of these and other minerals, it has been concluded that the main current which brought the materials of the Pebble-bed came from the south, but was enforced by tributaries from the west.

The North-Western District

The Triassic beds of Cheshire and Lancashire are in general similar to those of the Midlands. The same divisions can be recognised, but they attain a greater development.

The Keuper marls contain several beds of rock-salt and gypsum, which are worked most extensively in Cheshire. At Northwich the salt is mined, but elsewhere it is usually obtained by admitting water and pumping up the brine.

Over the greater part of the area the top of the Trias has been worn away, and consequently the Rhætic beds occur only around the outlier of Lias, which lies on the borders of Shropshire and Cheshire.

In the Vale of Eden and the northern part of Cumberland there is a considerable area of Triassic rocks. Here they may be divided as follows:—

3. Red marls with rock-salt and gypsum.
2. St. Bees Sandstone.
1. Gypsiferous marls with local conglomerate at base.

The marls at the base were formerly referred to the Permian system. There is no palæontological evidence of their age, but according to the late Mr. J. G. Goodchild they lie unconformably upon the undoubted Permian beds below, and consequently should be grouped with the Trias beds above.

The Rhætic series has not been proved in this district, but, as there is an outlier of Lias near Carlisle, it probably exists.

North-Eastern District

The north-eastern prolongation of the Trias where it joins the Midland area is naturally similar to the latter in character. The same divisions may be recognised, excepting that the Upper Variegated Sandstone cannot be distinguished.

Northwards, however, the distinctive features of the Bunter disappear, and the limits of the Bunter and the Keuper have not been defined. In North Yorkshire the Trias may be divided lithologically as follows:—

Rhætic series.
Red marls.
Red and white sandstone.
Red marls with rock-salt and gypsum.

The Rhætic series presents its usual character, but it is by no means clear how much of the remainder belongs to the Keuper and how much to the Bunter.

Scotland

The post-Carboniferous red sandstones of Southern Scotland, with their associated volcanic rocks, have already been described along with the Permian deposits; but they have yielded no fossils, and may possibly belong to the Triassic system.

Small patches of undoubted Trias occur in the Western Islands and upon the Western Coast; but by far the most interesting of the Scottish Triassic rocks are the Elgin sandstones, which are found on the Elgin coast near Lossiemouth. They lie unconformably upon the Old Red Sandstone, and have yielded a remarkable series of reptilian remains, including Dicynodonts (e.g. *Gordonia* and *Geikia*), Rhynchocephalia (*Telerpeton* and *Hyperodapedon*), and crocodiles (e.g. *Stagonolepis* and *Ornithosuchus*).

Ireland

In Ireland the Trias is found only in the north-eastern part of the country. The largest area is that of Belfast Lough, extending up the valley of the Lagan. Other patches occur at intervals around the margin of the great basaltic plateau of Antrim. They consist of red and brown sandstones and marls with gypsum and rock-salt, followed by grey shales with a Rhætic fauna.

CHAPTER XXV

THE JURASSIC SYSTEM

THE Jurassic beds of England (Fig. 119) form an almost continuous belt stretching from the coast of Yorkshire south of the Tees to the Dorset coast about Lyme Regis and Weymouth. The breadth of the belt varies considerably. It is widest towards the middle, where it spreads from the neighbourhood of Leicester to King's Lynn in Norfolk; but in this region it is partly covered by the alluvial deposits of the Fens. It is narrowest in South Yorkshire, where, indeed, for a short distance it is completely overlapped by the Cretaceous beds.

Near the Bristol Channel there are many patches which are now cut off from the main band. At a greater distance are the outliers of Lias on the border of Cheshire and in Cumberland near Carlisle.

That, originally, the Jurassic deposits had a very much wider extension is shown by the occurrence of small patches in the north-east of Ireland, in the Inner Hebrides, and upon both the western and the eastern coasts of Scotland.

Lithologically, the system consists chiefly of clays and limestones. Most of these are marine in origin, but some are estuarine or fluviatile, and occasionally there are even remains of terrestrial soils. Some of the subdivisions pass almost unaltered throughout the length of England, but others show considerable variations.

The general character of the changes will be most readily understood if we take the southern development as a type. Here the system consists of an alternating series of clays and limestones (Fig. 120). The divisions which in the south consist of clay, remain clay throughout the whole of England. The divisions which are calcareous in the south, change their character as they are traced towards the north. The changes are shown in the following table, in which, it must be understood, only the general character of the deposits is indicated:—

	South of England.	Middle of England.	North of England.
Purbeckian, Portlandian . .	limestone	absent	absent ?
Kimeridgian . .	clay	clay	clay
Corallian . .	limestone	clay	limestone
Oxfordian . .	clay	clay	clay
Bathonian, Bajocian (Lower Oolites.)	limestone	limestone sands	sands
Lias . .	clay	clay	clay

Fauna and Flora.—Since the system consists chiefly of marine deposits, the greater number of the fossils are marine, but estuarine and

FIG. 119.—THE JURASSIC SYSTEM.

terrestrial forms occur. The period has been called 'the Age of Cycads,' 'the Age of Ammonites,' and 'the Age of Reptiles,' according to the point of view of the writer; and these three names indicate the most striking features of the fauna and flora.

Plants are found at several horizons, and especially in the estuarine and terrestrial deposits. Undoubtedly the special characteristic of the period is the predominance of cycads, such as *Williamsonia* and *Nilssonia*, and ferns. Conifers are also well represented.

Corals are abundant in the limestones, but rare in the clays. The rugose corals of the Palæozoic period have disappeared, and in their place are aporose and perforate types. Amongst the common genera are *Montlivaltia*, *Isastrea*, *Thecosmilia* and *Thamnastræa*.

Of the Echinoderma the crinoids are relatively much less abundant than in the Palæozoic rocks, while the echinoids have become far more important. The crinoids include *Pentacrinus* and *Apiocrinus*. The echinoids, which occur chiefly in the limestones, include *Cidaris*, *Hemicidaris*, *Acrosalenia*, *Nucleolites* (=*Echinobrissus*), *Holectypus* and *Pygaster*.

Brachiopods are still common, but nevertheless they no longer preponderate as in the Palæozoic era. The period is characterised by the large number of species and individuals belonging to the genera *Terebratula*, *Magellania* and *Rhynchonella*.

Of the Mollusca, lamellibranchs, gastropods and cephalopods are all abundant. The most striking feature of the period is the great development of the ammonites, which occur both in the clays and in the limestones. So abundant and so widespread are they, and so varied in form, that they serve to divide the system into zones which can be recognised over a large part of the globe. Belemnites also appear, and attain their maximum in this period. They are found chiefly in the clays.

So far as vertebrates are concerned, the period was certainly the age of reptiles. They played the dominant part in the sea

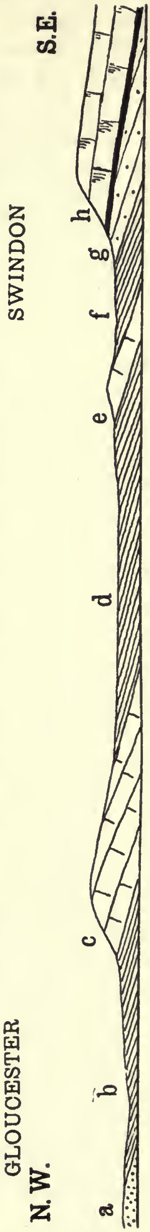


Fig. 120.—Diagrammatic Section from Gloucester to Swindon.

a, Trias; *b*, Lias; *c*, Lower Oolites; *d*, Oxford Clay; *e*, Corallian; *f*, Kimeridge Clay; *g*, Portland and Purbeck beds; *h*, Cretaceous.

(Ichthyopterygia, Sauropterygia), on the land (Dinosauria) and in the air (Pterosauria).

The earliest known birds occur in the Jurassic system, two skeletons having been found at Solenhofen, in Germany. They are known as *Archæopteryx.* The tail was composed of a number of separate vertebræ, with a pair of feathers to each.

Mammalia are found in England in the Stonesfield Slate (Bathonian) and in the Purbeck beds. Most of the forms appear to have been marsupials, but some probably belong to a more primitive group (Prototheria).

The Lias

The Lias is essentially an argillaceous formation. It consists chiefly of grey or blue-grey clays or shales, which give rise to some of the richest pasture-lands of England. Occasionally the clays are sandy; more often they are calcareous or marly. Beds of limestone are sometimes abundant, especially in the lower part of the series; but the Liassic limestones are quite unlike the limestones of the Carboniferous and Silurian systems. They are not coral-reefs, nor are they often shell-banks. Most of the bands, indeed, are only indirectly of organic origin. They consist largely of detrital material, which seems to have been derived from the denudation of pre-existing limestones. They were, in fact, calcareous muds laid down near the shores of an old land in which the Palæozoic limestones were prominently exposed. In consequence of this mode of formation, the Liassic limestones are seldom pure. They are almost always argillaceous or ferruginous. They seem, moreover, to have been deposited in shallower water than the clays. The summits of the Mendip Hills rose as islands above the Liassic sea, and near the Mendip ridge the limestones thicken at the expense of the clays. The fossils also indicate the neighbourhood of land. Several of the limestone bands contain remains of winged insects in such abundance that they are locally known as 'insect limestones.'

In some districts the Lias includes valuable beds of iron-ore, and sometimes there are seams of lignite or masses of jet. Pyrites is often abundant, and the shales may then serve as a source of alum.

Although the sands and limestones appear to indicate the neighbourhood of land, the whole of the Lias was laid down beneath the sea. The insects which are found in certain beds are associated with ammonites and other shells, and everywhere the fauna of the Lias is distinctly marine. But, even in the limestones, it was the fauna of a muddy sea.

Corals, echinoids and polyzoa are rare. A few genera of crinoids, however, such as *Pentacrinus* and *Extracrinus*, are locally abundant.

Brachiopods are common, *Spiriferina Walcotti* and *Rhynchonella tetrahedra* being two of the characteristic species.

Gastropods are not abundant, and by far the most prominent of the Mollusca are the lamellibranchs and ammonites. The lamellibranchs include *Gryphœa arcuata* (perhaps the most common of all the Lias fossils), *Hippopodium ponderosum*, *Lima gigantea* and *Nuculana ovum*. The ammonites are used as zone-fossils, and the names of the principal species will be found in the list of zones given below.

The insects have already been referred to. They include representatives of several of the living orders, such as Orthoptera, Diptera, Neuroptera, Coleoptera and Hemiptera.

Many genera of fish occur; but the most remarkable of the vertebrates are the reptiles. Amongst these are the large saurians, such as *Ichthyosaurus* and *Plesiosaurus*, which lived in the sea; and the flying Pterodactyls, such as *Dimorphodon*.

Plants are not very common; but they occur in several localities. Cycads are the predominant group.

The Lias is divided into a number of zones, each of which is characterised by the occurrence of a particular species of ammonite. The grouping adopted by the Geological Survey is as follows:—

Upper Lias .	Zone of	*Ammonites*	*jurensis.*
	,,	,,	*communis.*
	,,	,,	*serpentinus.*
Middle Lias .	,,	,,	*spinatus.*
	,,	,,	*margaritatus.*
Lower Lias .	,,	,,	*capricornus.*
	,,	,,	*Jamesoni.*
	,,	,,	*oxynotus.*
	,,	,,	*Bucklandi.*
	,,	,,	*planorbis.*

Most of these zones admit of further subdivision. Many geologists include the *capricornus* and *Jamesoni* zones in the Middle Lias.

Lithologically, the general character of the Lias remains unchanged from Dorsetshire to the Yorkshire coast; but there are variations in detail, some of which are of considerable importance.

South of England.—In the south of England the succession is as follows:—

Upper Lias. Clays or shales, becoming sandy towards the top, and with a pale-coloured argillaceous limestone at the base.

Middle Lias. Micaceous sandy clays with a ferruginous limestone, the 'Marlstone,' at the top.

Lower Lias. Grey marls and clays, with bands of limestone.

Generally the limestones predominate at the base of the series, and the Lower Lias may often be divided into a calcareous division below and an argillaceous division above; but the development of the limestones is irregular, and no definite boundary can be drawu between the two divisions.

The Middle Lias is less calcareous and more sandy; but the marlstone at the top, though thin, is very persistent. The clays and sands belong generally to the *Ammonites margaritatus* zone, the marlstone to the zone of *Ammonites spinatus*.

The limestone at the base of the Upper Lias contains remains of reptiles, fish, crustaceans and insects, together with marine fossils. This is followed by clays and shales, which become sandy towards the top; and frequently there is a considerable thickness of sands between the Upper Lias Clays and the limestones of the Inferior Oolite. But the horizon at which the sands begin is variable, and their upward limit is inconstant. In some places the highest zones of the Lias consist of clay. In other cases the sands have been removed by denudation before the deposition of the succeeding series.

Midlands.—In the Midlands the same general succession can be recognised. The Lower Lias consists chiefly of limestones below, mainly of clays above. The Middle Lias is formed of micaceous sands and clays, capped by the marlstone. The Upper Lias commonly begins with an insect limestone, and this is followed by clays and shales; but the shales no longer pass upwards into sands. The junction with the Inferior Oolite is sharply defined, and sometimes presents evidence of erosion.

Lincolnshire and Yorkshire.—Towards the north certain lithological changes occur. As far as Market Weighton there is a considerable development of argillaceous limestones at the base; but in the north of Yorkshire the whole of the Lower Lias consists principally of shales with thin bands of shelly limestone.

But the most remarkable feature of the northern area is the conversion of many of the limestones into seams of iron-ore. The change, indeed, is not unknown in the Midlands, where occasionally the marlstone contains enough iron to be of commercial value. But the beds of iron-ore increase in number and importance towards the north.

The first stage in the alteration of the limestones appears to have been the replacement of the carbonate of lime by ferrous carbonate. Subsequent oxidation has sometimes converted the latter into ferric oxide (hæmatite) or hydrated ferric oxide (limonite).

The iron-ore of Frodingham, in Lincolnshire, lies in the Lower Lias, and consists of rather thin-bedded alternations of limonite and ferruginous limestone.

It is, however, in the Middle Lias of North Yorkshire that the development of iron-ore has been carried to the greatest extent. There the Middle Lias may be divided into a Sandy Series below and an Ironstone Series above. The Sandy Series includes the lower part of the *Ammonites margaritatus* zone, and extends downwards into the zone of *Ammonites capricornus* (Lower Lias). It consists of alternations of hard sandy shales and thin, micaceous, calcareous and ferruginous sandstones. The Ironstone Series includes the upper part of the *Ammonites margaritatus* zone and the whole of the *Ammonites spinatus* zone, and consists of numerous alternations of shale and ironstone. It is from these beds that the greater part of the Cleveland iron-ore is obtained. The principal band of ironstone is the Cleveland Main Seam, which contains *Ammonites spinatus* and appears to be the equivalent of the marlstone.

Other seams are also worked. In general the ironstone bands are thickest and most important towards the north-west, while towards the south and east they split and gradually die out.

The Upper Lias of Yorkshire consists almost entirely of micaceous shales, with occasional thin hard bands which may be calcareous, ferruginous, or sandy. Near Whitby it may be divided lithologically into—

Alum shales . . .	*Ammonites communis* zone.
Jet shales . . .	*Ammonites serpentinus* zone.
Grey shales . . .	*Ammonites annulatus* zone.

The *Ammonites jurensis* zone has not been found except between Blea Wyke and Peak.

The jet of the *Ammonites serpentinus* zone occurs as isolated lumps, and is very irregular in distribution. It is presumably of vegetable origin; but the mode of formation is not understood.

The alum shales are grey crumbly shales with much disseminated pyrites, which causes a yellow incrustation on the weathered fragments. These shales were formerly extensively used for the manufacture of alum, but the industry is now extinct in this district.

Scotland.—That the Lias sea extended into Scotland is shown by the occurrence of Liassic deposits, in part marine, in the Inner Hebrides, and upon both the west and east coasts of the mainland—upon the eastern coast as far north as Dunrobin Castle in Sutherland. But there are clear indications that these deposits were laid down near the margin of the ancient sea. Upon both coasts the lowest beds are either estuarine or littoral in origin, consisting largely of sands and conglomerates. The upper part of the Lower Lias, on the other hand, and both the Middle and the Upper Lias, where they are present, are marine, and do not differ very greatly from the corresponding beds in England.

In the Western Isles and on the Western Coast the Mesozoic rocks owe their preservation in part to faulting, but chiefly to the protection afforded by the great lava-flows of the Tertiary era. They are exposed, therefore, only where the overlying basalts have been removed by denudation, and continuous sections are rare. The finest is that upon the east coast of the island of Raasay.

The actual base of the Lias is not seen, but at Applecross there are indications of an estuarine series in which a seam of coal is said to have been once exposed. Above this are limestones, sandstones, grits and conglomerates, which were evidently laid down in shallow water. They have not yielded ammonites, but the fossils are marine, including such forms as *Ostrea cingulata* and *Cardinia concinna*, and they are believed to represent the zone of *Ammonites planorbis* and a part of the following zone. The rest of the Lower Lias, wherever it is found, consists chiefly of limestone and shale, with ammonites, and was laid down in a deeper sea.

The Middle Lias consists of calcareous sandstones; the Upper Lias of laminated blue clay with pyrites and jet.

On the East Coast the Lower Lias is found at Dunrobin Castle, in Sutherland. The lowest beds are sandstones, shales and beds of coal, and are evidently of estuarine origin. These are followed by sandstones, limestones and clays with a marine fauna; but many of the shells are dwarfed, as if they lived in brackish water. The remainder of the Lower Lias is undoubtedly marine, and contains fossils of the *Ammonites oxynotus* and succeeding zones.

The Middle Lias has not been found in situ. But boulders with Middle Lias fossils are so abundant in the glacial clays of Elgin that their source can hardly have been far away.

Ireland.—In Ireland, as in the Western Isles, the Lias owes its preservation to the outflows of Tertiary lava which overspread the north-eastern part of the country. It is accordingly only around the margin of the Antrim plateau that any deposits of this period are found. They consist of shales, clays, and limestones, with typical Lower Lias fossils. No trace of the Middle or Upper Lias has been found, and even the higher zones of the Lower Lias are not seen.

The Lower Oolites

In the south of England the Lias is succeeded by a series of limestones, with intercalated clays and sands, which have long been grouped together under the name of the Lower Oolites. Often there is no sharp boundary between the two formations; but in some districts the upper beds of the Lias were removed before the deposition of the Oolites.

Although consisting largely of calcareous rocks, the Lower Oolites are shallow-water deposits. The limestones are usually oolitic or pisolitic, and as a rule they are conspicuously current-bedded. The sands, too, are generally false-bedded, and it is only the occasional beds of clay that appear to have been laid down in tranquil waters. Everywhere in the south of England the deposits are marine, but they were formed in a shallow sea disturbed by changing currents. Owing to the fluctuations of these currents the individual beds are somewhat inconstant, and frequently there are gaps in the succession. In some cases the gaps may be due simply to absence of deposition, but sometimes a temporary increase in the strength of the currents has resulted in the removal of a part of the material which was already laid down. In Gloucestershire there is evidence of gentle flexuring of the sea-floor in the midst of the period. The flexures did not raise the beds above the sea, but the currents removed the tops of the shallow anticlines, and consequently the later members of the series rest with a slight unconformity upon the beds below.

As the Lower Oolites are traced northwards along the Jurassic outcrop they lose their calcareous character and the limestones are replaced by sands. The sands at the base are usually marine, but in Northamptonshire and Rutland estuarine deposits appear above them, and the estuarine facies becomes more and more pronounced towards the north. The changes are very complex, and are shown diagrammatically in Fig. 121.

In accordance with the lithological variation there is a corresponding change in the fossils, and thus it is impossible to distinguish in the north of England the minor subdivisions which have been recognised in the south.

In the south, where calcareous beds predominate, ammonites, gastropods, lamellibranchs, brachiopods and echinoids are abundant. Corals and polyzoa are plentiful in some beds, and many sponges have been obtained. On the other hand, plants, crustaceans, insects and vertebrates are rare except in the Stonesfield Slate. In this deposit, however, a remarkable fauna has been discovered, including mammals (*Amphilestes*, *Phascolotherium*, &c.), ornithosaurs and other reptiles, fish, crustaceans, insects, marine mollusca, &c., together with remains of plants.

In the Estuarine series of the north of England there are occasional bands with marine fossils; but the estuarine beds themselves contain chiefly plants and fresh-water shells. The common genera are the ferns, or fern-like forms, *Cladophlebis*, *Todites*, *Coniopteris*, *Laccopteris*, &c., and the cycads, *Williamsonia* and *Otozamites*.

In the south of England the Lower Oolites may be divided into a number of zones by means of the ammonites, but it is impossible to

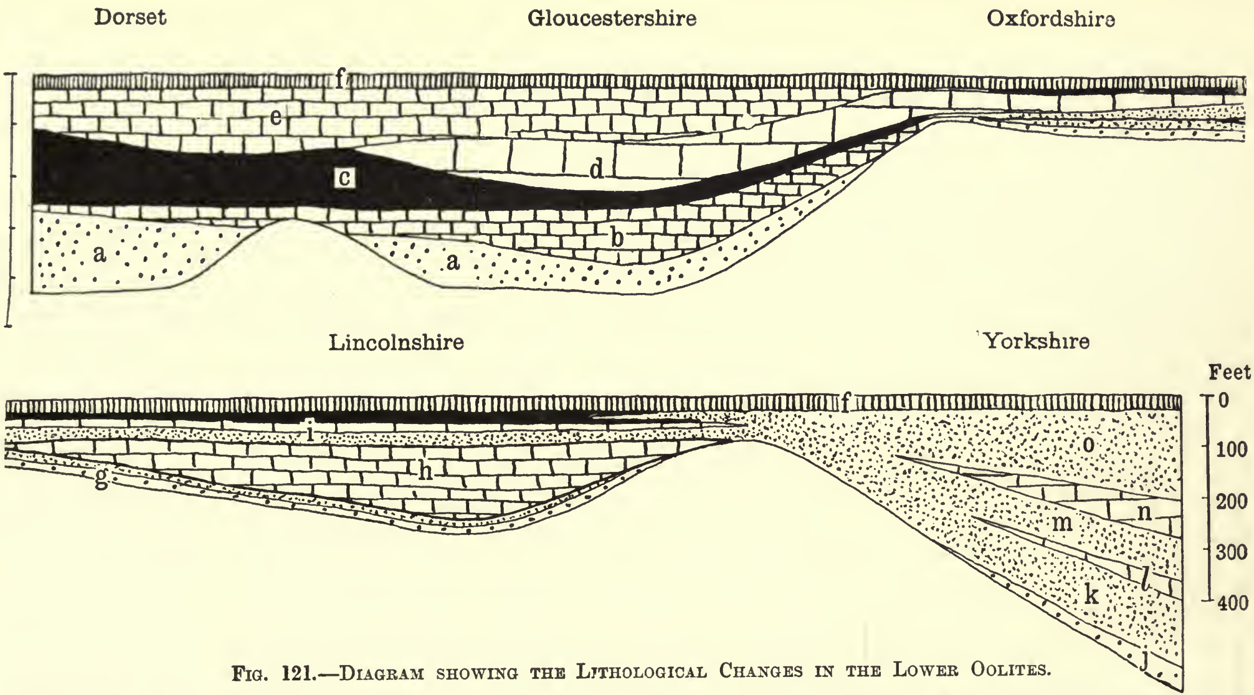


FIG. 121.—DIAGRAM SHOWING THE LITHOLOGICAL CHANGES IN THE LOWER OOLITES.

South of England: *a*, Midford Sands (belonging in part to the Lias); *b*, Inferior Oolite; *c*, Fuller's Earth; *d*, Great Oolite; *e*, Forest Marble; *f*, Cornbrash.

Lincolnshire: *g*, Northampton Sands and Lower Estuarine Series; *h*, Lincolnshire Limestone; *i*, Upper Estuarine Series, Great Oolite Limestone, Great Oolite Clay; *f*, Cornbrash.

Yorkshire: *j*, Dogger; *k*, Lower Estuarine Series; *l*, Millepore Limestone; *m*, Middle Estuarine Series; *n*, Scarborough Limestone; *o*, Upper Estuarine Series; *f*, Cornbrash.

carry these zones into the north of the country. It is customary to divide the groups into a lower division, the Inferior Oolite series or Bajocian, and an upper division, the Great Oolite series or Bathonian, but even this broad grouping can hardly be maintained in the north.

The South-western District.—The south-western district includes Dorsetshire, Somersetshire, Gloucestershire and a part of Oxfordshire. In spite of local variations, the following subdivisions may generally be recognised:—

Great Oolite Series .	Cornbrash. Forest Marble and Bradford Clay. Great Oolite, with the Stonesfield Slate. Fuller's Earth.
Inferior Oolite Series .	Inferior Oolite. Midford sands (in part).

Palæontologically, the Inferior Oolite series may be divided into four zones, namely, in descending order:—

4.	Zone of	*Ammonites*	*Parkinsoni.*
3.	„	„	*Humphriesianus.*
2.	„	„	*Murchisonæ.*
1.	„	„	*opalinus.*

A much more minute subdivision is possible in this district, but even the four zones here mentioned cannot be distinguished in the north of England.

Lithologically, the series is divided into the Midford sands below and the Inferior Oolite limestone above. But the sands which lie between the limestone and the Upper Lias Clays are not everywhere at the same horizon; and there is accordingly considerable practical difficulty in drawing the boundary between the Lias and the Oolites. Conventionally the line is taken between the zones of *Ammonites jurensis* and *Ammonites opalinus*, and in that case the sands belong for the most part to the Lias, but in Dorsetshire they extend upwards into the Inferior Oolite series. In the northern Cotteswolds, on the other hand, this series is calcareous or marly to its base.

A somewhat remarkable feature of the Inferior Oolite is the existence in Gloucestershire of a distinct unconformity in the midst of the series. In the northern Cotteswolds the *Ammonites Parkinsoni* zone lies upon different subdivisions of the *Ammonites Humphriesianus* zone, while south of Bath it rests in turn upon the lower zones, upon the Lias and Rhætic, and finally upon the Carboniferous Limestone of the Mendip range.

The Great Oolite series also consists chiefly of oolitic limestones, but there are considerable local variations in its development.

The lowest member of the series is the Fuller's Earth. It is a marly clay, blue, grey or yellowish in colour, but only the upper part yields the fuller's earth of commerce. The middle is often an earthy limestone, which is locally called the Fuller's Earth rock. Amongst the characteristic fossils are *Ammonites subcontractus* and *Ostrea acuminata.* In Dorsetshire the Fuller's Earth is about 150 feet thick, but north and north-east of Bath it diminishes in thickness, and in Oxfordshire it becomes scarcely separable from the Stonesfield Slate.

The Great Oolite limestone, or Great Oolite proper, consists of shelly limestones or 'rags,' and fine oolites or freestones, with occasional layers of sandy marl. It attains a considerable thickness in Gloucestershire, where it yields the well-known Bath stone; but in Dorsetshire it becomes extremely thin or altogether dies out. As the Fuller's Earth thickens in this direction, it has been suggested that the two formations may be in part contemporaneous; but it is probable that the absence of the Great Oolite in the south is due in part to erosion.

The lower part of the Great Oolite is in general more sandy and flaggy than the upper, and it is to this part, where the flaggy structure is well developed, that the name of Stonesfield Slate has been applied. The most remarkable feature of the Stonesfield Slate is that it has yielded remains of mammalia, reptiles, fish, insects and plants, as well as the usual marine fossils of the Great Oolite.

The zone fossil of the Great Oolite is *Ammonites arbustigerus.* Amongst other common species are *Terebratula maxillata* and *Acrosalenia hemicidaroides.*

The Forest Marble, together with the Bradford Clay, is a very variable series. It consists of shelly oolitic limestones, thin flaggy limestones, clays and shales, with, in some places, beds of sand. Near Bradford-on-Avon and other places the lower beds are clay with an abundance of fossils, and form the so-called Bradford Clay; but the Bradford Clay is no more than a local facies of the Forest Marble.

In Gloucestershire the Forest Marble rests upon the Great Oolite, but south of the Mendips it overlaps that formation and lies directly on the Fuller's Earth.

The common fossils of this subdivision are *Magellania digona, Rhynchonella varians, Terebratula coarctata* and *T. maxillata. Apiocrinus Parkinsoni* is abundant in the Bradford Clay, but it grew upon the Great Oolite, and apparently was killed by the incursion of the muds which now form the Bradford Clay.

The Cornbrash is the most uniform of all the subdivisions of the Lower Oolites, and the only one which stretches almost unaltered along the length of England. Everywhere it consists of tough irregular layers of earthy and shelly limestone, with partings of marly and sandy clay; and where it is exposed in quarries it usually presents a very rubbly appearance. There is an absence of the marked false-bedding so conspicuous in the beds below, and it was evidently deposited in more tranquil waters. Its thickness is generally from 10 to 25 feet. *Ammonites macrocephalus, Terebratula intermedia* and *Magellania lagenalis* are amongst the characteristic fossils.

Central District.—The Central District may be taken to extend from Oxfordshire to the north of Lincolnshire.

From Dorsetshire to the north of Gloucestershire the outcrop of the Lower Oolites runs from south to north; but here the direction changes, and through Oxfordshire the trend is more nearly from west to east. With the alteration in direction there begins a change in the nature of the deposits. Towards Fawler, in Oxfordshire, the whole series rapidly decreases in thickness, and the lower members of the Inferior Oolite are completely overlapped. Beyond Fawler the lower beds reappear; but their character is altered. At the base are brown ferruginous sands and calcareous sandstones. At first very thin, these sandy beds thicken towards the north-east, and are known as the Northampton Sand.

As the Northampton Sand develops at the base of the Inferior Oolite, the rest of that series is replaced by lighter coloured sands with plant-remains. These are of estuarine origin, and are known as the Lower Estuarine series.

A similar change takes place in the lower part of the Great Oolite series, and the general result of all these changes is that from Northamptonshire to Lincolnshire the Lower Oolites may be divided as follows:—

Cornbrash.
Great Oolite Clay.
Great Oolite Limestone.
Upper Estuarine Series.
Lincolnshire Limestone with the Collyweston Slate.
Lower Estuarine Series.
Northampton Sand.

There are, however, local gaps in the succession.

The Northampton Sand includes beds of hard calcareous sandstone, ironstone and occasional sandy oolitic limestones. The thickness is variable, but probably never exceeds forty feet. Fossils are not often abundant. They are mostly marine forms, and amongst them are the zone ammonites *A. jurensis*, *A. opalinus* and *A. Murchisonæ*. Apparently, therefore, the series is in part of Liassic age, but in general it rests upon an eroded surface of the Lias Clay. Economically, the Northampton Sand is important on account of the valuable beds of iron-ore which it contains.

The Lower Estuarine series consists of white, brown and grey sands, with inconstant beds of clay. Remains of plants occur, but other fossils are rare.

In North Oxfordshire and a large part of Northamptonshire these beds are followed directly by the Upper Estuarine series. The junction is there an eroded one, and there is often a distinct unconformity between the two series. North of the Welland, however, a thick mass of limestones intervenes and the unconformity disappears. This is the Lincolnshire Limestone, which has yielded the famous Barnack and Ketton building stones. The Collyweston Slate is merely the name applied to the beds of fissile sandy limestone which occur at its base. The Lincolnshire Limestone contains numerous marine fossils, and has been referred to the zone of *Ammonites Murchisonæ;* but some of the fossils suggest that the higher zones of the Inferior Oolite may also be represented.

The Upper Estuarine series consists of blue, purple, white and variegated clays, more or less sandy, with occasional irregular layers of limestone. They contain chiefly plant remains and fresh-water shells such as *Cyrena* and *Unio;* but marine fossils are also found.

The Great Oolite Limestone and Great Oolite Clay are both marine deposits, and probably represent the Forest Marble and a part of the Great Oolite of the south-western district.

The Cornbrash presents the same general characters as in the south.

Yorkshire.—In Yorkshire the estuarine facies of the Lower Oolites attains its maximum development. The beds at the base, however, are still marine, and the Cornbrash retains its usual character. Moreover, the estuarine deposits are divided into three series by two intercalated marine bands. The succession is as follows :—

Cornbrash.
Upper Estuarine Series.
Scarborough Limestone.
Middle Estuarine Series.
Millepore Limestone.
Lower Estuarine Series.
Dogger.

The Dogger, which corresponds approximately, no doubt, with the Northampton Sand, is a very variable formation. It includes beds of sandstone, limestone and shale, and valuable bands of iron-ore, and it is often nodular or concretionary in structure. Usually the uppermost zone of the Lias is absent beneath the Dogger, and there must be a certain amount of unconformity between the two series. But at Blea Wyke Point, near Ravenscar, below the Dogger proper, there is a series of yellow and grey sands with Lower Oolite fossils, passing downwards into the *Ammonites jurensis* zone of the Upper Lias. Within a mile to the west the Blea Wyke beds have entirely disappeared, and the Dogger rests upon an eroded surface of the Lias. The disappearance of the Blea Wyke beds coincides with a considerable fault known as the Peak fault; and it is believed that this fault was being formed during the deposition of the beds. On the north-west side the sea-floor was raised within the reach of waves and currents, and erosion took place; on the south-east side deposition was continuous from the Lias to the Oolites.

The Estuarine beds consist of irregular alternations of sandstone and shale, with thin seams of coal and occasionally a little ironstone. The Lower series is the most arenaceous of the three, and the upper the most shaly. Plant remains are found in all, but they are particularly abundant and well preserved in the Middle series, while the Upper series is almost barren except towards its base. *Cladophlebis*, *Coniopteris* and *Otozamites* are the commonest genera in the Lower Estuarine series; *Cladophlebis*, *Laccopteris*, and *Nilssonia* in the Middle Estuarine series.

The Millepore bed and the Scarborough Limestone are not the only marine bands which occur in the Estuarine series, but they are the most important. The Millepore Limestone on the coast is not a true limestone. It is a hard calcareous sandstone with ferruginous partings. Inland, however, it is composed in part of oolitic limestone. It derives its name from the small polyzoan *Entalophora* (*Millepora*) *straminea*, which in some places crowds the surface of the beds.

The Scarborough Limestone is the most important marine series in the Lower Oolites of Yorkshire. It includes, however, but little real limestone, and consists chiefly of calcareous shales and sandstones, and occasional coarse grits.

The Cornbrash is a thin band of hard ferruginous limestone passing down into calcareous shale. It contains the characteristic Cornbrash fossils *Magellania lagenalis*, *M. obovata*, &c., but it is found only in North Yorkshire. South of a line drawn west from Filey, the Estuarine series is followed directly by the Oxfordian.

Scotland.—Upon the western coast and in the Inner Hebrides the Lower Oolites are found in many places, from the Shiant Islands on the north to Ardnamurchan on the south. The best exposures are those in the islands of Raasay and Skye.

The Inferior Oolite series consists chiefly of sandstones and shales, with a limestone made of comminuted shells at the top. Ferns and cycads occur, and some of the beds are probably estuarine; but the greater part of the series contains marine fossils.

The Great Oolite series, on the other hand, seems to be almost entirely a fresh-water deposit. It consists at the top and bottom of dark shales with thin bands of limestone, and in the middle a great mass of sandstones and grits. The shales and limestones contain fresh-water shells (e.g. *Viviparus, Cyrena*) and ostracods (*Cypris*), but in the upper series there are beds completely made up of *Ostrea hebridica*. The sandstones have yielded little excepting remains of plants. Towards the base of the series numerous fish and reptilian remains have been found.

On the eastern coast the Lower Oolites occur near Brora, in Sutherland, and there are one or two smaller patches in Elgin. They consist chiefly of sandstones and shales, with layers of limestone and some thin seams of coal. The fossils are mostly fresh-water shells, plants, and the teeth and scales of fish. But *Ostrea* is also common. Probably, like the similar deposits on the western coast, they correspond with the Great Oolite series.

The Oxfordian Series

The variable group which has just been described is followed conformably by a much more uniform series known as the Oxfordian. It consists for the most part of bluish, greenish, or lead-coloured clay, which usually becomes brown or yellowish at the surface. Generally the lower part is more or less laminated and shaly, but the upper part often shows little signs of bedding. Calcareous bands and irregular lines of septaria occur, and, as in most of the great clay formations, there is often much pyrites and selenite.

Towards the base of the clay there are inconstant beds of sand and calcareous sandstone, often with a more or less marked concretionary structure. In some areas these sandy beds become so prominent that they have received a special name, and the Oxfordian is divided lithologically into two divisions—

2. Oxford Clay.
1. Kellaways Rock.

But the development of the sandy deposits varies considerably, and accordingly the line between the Kellaways Rock and the Oxford Clay does not run along a constant horizon.

The general uniformity of the Oxford Clay, the fineness of the material and the absence of false-bedding indicate a deeper sea than that in which the Lower Oolites were deposited—a sea so deep or tranquil that the sediments lay beneath the limits of action of waves and currents.

The fossils of the Oxfordian are naturally such as lived in a muddy sea. Corals and echinoderms are rare. Neither brachiopods nor gastropods are particularly common, although some species are occasionally found in abundance. It is the lamellibranchs, especially the oyster-like forms, and the cephalopods, both ammonites and belemnites, that constitute the most characteristic part of the Oxfordian fauna. *Gryphœa dilatata* is one of the commonest fossils in the upper beds, while *G. bilobata* is found in the Kellaways Rock. Of the belemnites, *B. Oweni* is the species which is most widely known. The ammonites, as in the other clay formations of the Jurassic system, serve as zone-fossils.

Macrurous crustacea are fairly common, but brachyurous forms are rare.

Fish are not very abundant. Remains of reptiles, such as *Megalosaurus*, *Ichthyosaurus*, *Pliosaurus*, &c., are found.

Fragments of plants are sometimes numerous, but the species are unrecognisable.

Palæontologically, the Oxfordian series is divided into four zones—

4. Zone of *Ammonites cordatus*.
3. " " *Lamberti*.
2. " " *Jason*.
1. " " *calloviensis*.

The zone of *Ammonites calloviensis* coincides approximately with the sandy beds at the base known as the Kellaways Rock.

The second and third zones are by some authors grouped together as the zone of *Ammonites ornatus*.

Owing to the general uniformity of the series, it is unnecessary to give any separate account of its development in different parts of England. Over most of the country it varies only in thickness and in the amount of arenaceous material at the base.

In Yorkshire, however, the facies of the Kellaways Rock extends upwards into the zone of *Ammonites Jason*, and the Oxford Clay loses its typical character and becomes a grey sandy shale in which fossils are generally rare. The total thickness is considerably less than in the south.

Scotland.—In the islands of Skye and Eigg the Estuarine series, which is referred to the Great Oolite period, is followed by a mass of blue clays with subordinate bands of argillaceous limestone. They contain *Ammonites Lamberti*, *Ammonites cordatus*, &c., and clearly represent the Oxford Clay.

In Sutherland the Oxfordian series consists of black shales and sandy clays, with a calcareous sandstone at the base. The latter is evidently the Kellaways Rock, and contains the Kellaways fauna. The shales and clays above contain typical Oxfordian fossils.

The Corallian Series

The Corallian, like the Lower Oolites, is a variable series, and exhibits two distinct facies. In the south of England and in Yorkshire it consists chiefly of calcareous rocks, while from Bedfordshire to Lincolnshire it is formed almost entirely of clay. But both clay and limestone are marine, and in England there is no indication of estuarine conditions.

The calcareous facies consists in general of shelly limestones, current-bedded oolites, masses of coral, together with occasional layers of sand or clay. Ripple-marks and worm-burrows are found in some of the sands, and lignite is not uncommon. Such deposits must have been formed in a shallow sea where the water was clear and free from mud.

The argillaceous facies, on the other hand, consists of finer sediment and shows no false-bedding. It was probably laid down in deeper but more muddy water.

In the calcareous beds corals, echinoderms, gastropods and lamellibranchs are the most abundant forms. Ammonites and belemnites are also found. Brachiopods and polyzoa are comparatively rare. Of the corals, *Isastrea explanata*, *Thecosmilia annularis* and *Thamnastrea arachnoidea* are the species most often found. *Nucleolites scutatus* is the commonest of the echinoids; *Hemicidaris intermedia*, *Cidaris florigemma* and *Pygaster umbrella* are also frequently met with. The gastropods include *Nerinæa*, *Pseudomelania*, &c. *Trigonia clavellata* is one of the characteristic lamellibranchs. The principal ammonites are *A. perarmatus* and *A. plicatilis*, both of which serve as zone-fossils.

The argillaceous facies contains few corals or echinoderms. Lamellibranchs, ammonites and belemnites are the characteristic fossils. The fauna is, to a large extent, a mixture of Oxfordian and Kimeridgian forms, including, for example, the common Oxford Clay species *Gryphæa dilatata*, and the Kimeridge Clay species *Ostrea deltoidea*. But it includes also a certain number of the characteristic species of the calcareous Corallian. The commonest fossil is *Ostrea discoidea*.

Owing to the great variability of the deposits, the lithological sub divisions are only of local value. Palæontologically, the series may generally be divided into two zones—

2.	Zone of *Ammonites plicatilis*.	Upper Corallian.
1.	,, ,, *perarmatus*.	Lower Corallian.

South-western District.—In the south-west of England the Corallian consists of calcareous grits, rubbly, shelly and oolitic limestones, with occasional beds of clay. They may be grouped as follows:—

Upper Calcareous Grit and Upper Coral Rag . . . . Coral Rag and Coralline Oolite	Zone of *Ammonites plicatilis.*
Lower Calcareous Grit . .	Zone of *Ammonites perarmatus.*

The deposits are very variable. Generally, however, the Lower Corallian consists of calcareous sandstone, forming the 'Lower Calcareous Grit.' The Upper Corallian consists chiefly of shelly limestones (the Coral Rag [1]), oolitic limestones (the Coralline Oolite), and sometimes the top beds are arenaceous, forming an 'Upper Calcareous Grit.'

Over a considerable area in Wiltshire the upper beds have been converted into an oolitic ironstone, which was worked for many years at Westbury.

A few miles east of Oxford the limestones somewhat suddenly disappear. Here, probably, begins the argillaceous facies, though the Corallian clays have not yet been distinguished in the immediate neighbourhood.

Central District.—From the north-eastern part of Oxfordshire into Lincolnshire the Corallian series is represented for the most part by clay, known as the Ampthill Clay. In some places, for example at St. Ives in Huntingdonshire and Elsworth in Cambridgeshire, there is, at the base, a hard calcareous band with ferruginous oolitic grains. This band has now been traced for a considerable distance in Huntingdonshire and Cambridgeshire, and is generally called the Elsworth Rock. It is believed to represent approximately the Lower Calcareous Grit of the south of England (Fig. 124, p. 445).

The Ampthill Clay is darker in colour than the Oxford Clay, and contains more carbonaceous material.

At Upware, about nine miles north of Cambridge, there is a small isolated mass of coral rag and coralline oolite similar to the calcareous Corallian of the south of England, and containing a similar series of fossils. A small boring has shown that at the base there is a hard band of calcareous ferruginous oolite like the Elsworth Rock.

Yorkshire.—In the southern part of Yorkshire the Corallian, if present at all, is of the argillaceous type; but in North Yorkshire the calcareous facies is again developed, and indeed attains a greater thickness than in any other district in England. It forms a large part of the hills which encircle the Vale of Pickering.

[1] The term 'rag' is used somewhat vaguely. It appears to be applied to any hard shelly or coralline limestone which breaks irregularly.

Palæontologically, the same two zones may be recognised as in the south of England. The lithological subdivisions are—

Upper Calcareous Grit . .	Zone of *Ammonites plicatilis.*
Coral Rag and Upper Limestone .	
Middle Calcareous Grit . .	
Lower Limestone . . .	Zone of *Ammonites perarmatus.*
Passage Beds	
Lower Calcareous Grit . .	

Essentially it consists of three arenaceous series, the Lower, Middle and Upper Calcareous Grits, separated by beds of limestone. There are, however, considerable variations in the development and thickness of these subdivisions.

In this part of England there is a marked unconformity between the Corallian and the overlying Kimeridge Clay. In the hills east of the Derwent the clay in places rests directly upon the Lower Calcareous Grit.

Scotland.—No Jurassic deposits of later age than the Oxfordian series are found on the western side of Scotland. But on the eastern coast, in the Brora district, both the Corallian and the Kimeridgian are present.

The Corallian consists of limestones, clays and sandstones. Beds with marine fossils occur, especially at the base and towards the top, but the main mass of the series is a white sandstone with bands of lignite, and this is probably of estuarine origin.

The Kimeridgian Series

The variable Corallian series is followed by the Kimeridge Clay, or Kimeridgian, one of the most constant and uniform formations in England. It is a dark-grey or black shaly clay, which weathers brown upon its surface and often contains much selenite and pyrites. As a rule it is distinguished from the Oxford Clay by its darker colour and more shaly structure; also the layers of septaria are more frequent and more persistent. Occasionally the shales are highly bituminous, and sometimes there are bands of shaly limestone.

From Dorset to the Yorkshire coast the same lithological characters are preserved, and only the thickness varies. In the south of England the Kimeridge Clay is about 1,200 feet thick, in Oxfordshire only about 100 feet.

In England the Kimeridgian series was evidently deposited at a considerable distance from the shore. The sediment is always fine and without admixture of coarse material. But in the north of Scotland sands and grits and shelly limestones predominate.

Fossils are everywhere abundant. The dominant groups are those which flourish in a sea with a muddy bed. Corals and echinoderms are rare; gastropods are not very common. A few species of brachiopods are abundant, but the principal fossils are lamellibranchs and ammonites. *Aptychus* (probably the operculum of *Ammonites*) is very common. Numerous remains of reptiles have been found, including *Ichthyosaurus*, *Plesiosaurus*, *Pliosaurus*, various Dinosaurs and other forms. Fish teeth, spines and scales are not uncommon. In spite of the carbonaceous character of some of the beds, plants are rare, except in Scotland.

Owing to the general uniformity of the deposits no lithological subdivisions can be traced. Palæontologically, the series may be divided into two main zones:—

2. Zone of *Ammonites biplex* or Upper Kimeridge.
1. „ *Ammonites alternans* or Lower Kimeridge.

Amongst the common and characteristic fossils of the lower zone, besides the ammonites, are *Ostrea deltoidea*, *Astarte supracorallina* and *Rhynchonella inconstans*.

In the upper zone *Orbiculoidea latissima* is very abundant in some beds. *Exogyra virgula* is also very common, especially in the Upper Kimeridge, but it extends downwards into the lower zone.

On account of the overlap of the Cretaceous strata, the Kimeridgian does not form so continuous a belt as the earlier series of the Jurassic system. In Bedfordshire, for example, the Cretaceous beds spread over it and pass on to the Oxford Clay.

Scotland.—The Kimeridgian of the Brora district is an alternating series of sandstones, shales, limestones and grits. It is partly a marine and partly an estuarine deposit. Many of the Kimeridgian ammonites and other fossils have been found in it, and there is also an abundant flora, including ferns, cycads and conifers.

The Portlandian Series

Unlike the preceding subdivisions of the Jurassic system, the Portland beds have a very limited distribution, at least upon the surface. This is due, in the south of England, chiefly to the unconformable overlap of the Upper Cretaceous; and beneath the surface the Portland series may perhaps be continuous from Dorsetshire into Buckinghamshire. But from Bedfordshire to Norfolk no Portlandian beds are found, and there is no evidence that they exist below the Cretaceous covering. Remanié fossils belonging to the period are, however, common in some of the succeeding strata; and it is not improbable therefore that the Portlandian series may have been deposited even over this area, but was removed by denudation before the Cretaceous beds were laid down. In Lincolnshire and Yorkshire it is uncertain whether the Portlandian is or is not represented.

The rocks of this series are best displayed in the south of Dorsetshire, especially in the Isles of Portland and Purbeck. Farther north they are exposed at intervals along the margin of the Cretaceous outcrop, where the Cretaceous escarpment has been cut sufficiently far back. This is the case in the Vale of Wardour, the Vale of Pewsey near Devizes, at Swindon, and near Oxford and Aylesbury. But beyond Leighton Buzzard the series is unknown.

Lithologically, the Portlandian consists chiefly of limestones and sands. It is a marine deposit, and fossils are abundant in the limestones, somewhat less common in the sands. Although calcareous rocks form so large a part of the series, neither corals nor echinoderms are particularly common. One species of coral, however, *Isastrea oblonga*, is occasionally found in considerable abundance, almost always in a silicified condition. Brachiopods are rare. Gastropods, lamellibranchs and ammonites, the latter of enormous size, are the principal fossils. In the limestones the shell has often been dissolved away, and only the mould and cast are left. *Cerithium portlandicum*, *Trigonia gibbosa* and *Ammonites giganteus* are three of the commonest and best-known forms.

In Dorsetshire the Portlandian falls naturally into two divisions, viz. :—

2. Portland Stone or Upper Portlandian.
1. Portland Sand or Lower Portlandian.

The Portland Sand, which rests conformably upon the Kimeridge Clay, consists of yellow and greenish-grey sands with beds of loam and clay, and occasional layers of sandy or clayey limestone.

The Portland Stone consists chiefly of limestone, which may be shelly, oolitic, compact or chalky, with occasional sandy beds. Layers and nodules of chert are common in some of the limestones. It is from this series that the famous Portland building-stone is obtained.

In the Vale of Wardour the series retains the same general characters; but in the exposures farther north the upper division, as well as the lower, is composed chiefly of arenaceous deposits. At Swindon, for example, the limestones are comparatively thin, and the principal member of the Upper Portlandian is a mass of buff and white false-bedded sands with bands and lenticular layers of calcareous sandstone.

Although no undoubted Portlandian is known beyond Bedfordshire, it is still possible that the Spilsby Sandstone of Lincolnshire, and the base of the Speeton Clay in Yorkshire, may belong in part to this series. These deposits, however, are usually referred to the Cretaceous, and they will accordingly be dealt with in the account of that system.

The Purbeckian Series

In their distribution the Purbeck beds are closely connected with the Portlandian series. They are found in the south of Dorsetshire, in the Vale of Wardour, at Swindon, and in the neighbourhood of Oxford and Aylesbury. They do not appear in the Vale of Pewsey, but on the other hand they are exposed in the centre of the Wealden anticline, where the Portland beds do not reach the surface.

In general, the series rests conformably upon the Portlandian and passes up without a break into the Wealden beds above. But at Swindon there is a distinct unconformity between the Portland and the Purbeck beds. Locally, irregular and eroded junctions occur in the midst of the Purbeck series itself, but probably none of these indicate any considerable lapse of time.

The Purbeck series consists chiefly of shales, marls and limestones. There are also occasional bands of dark loamy earth, which are known as Dirt-beds. By far the greater part of the series is of fresh or brackish water origin. The Dirt-beds contain tree-stumps and other terrestrial remains, and appear to be ancient soils. Only one band is definitely marine. This is the 'Cinder-bed,' which occurs in the midst of the series, and which is made up almost entirely of the shells of *Ostrea distorta*.

The fauna of the series is very varied. Besides the shell already mentioned, *Hemicidaris purbeckensis* and other marine fossils occur in the Cinder-bed. In general, however, fresh-water, brackish-water and terrestrial animals and plants predominate. *Unio*, *Viviparus* (*Paludina*), *Physa* and *Limnæa* are abundant, especially in the upper beds. Ostracods, such as *Cypris* and *Cypridea*, occur throughout. The isopod *Archæoniscus Brodiei* is found in profusion in some localities. Insects of various kinds are numerous. Fish and reptiles are also often found. But perhaps the most remarkable of the fossils are the remains of mammalia which have been discovered at the base of the Middle Purbeck in Durlston Bay. These include *Plagiaulax, Triconodon, Spalacotherium* and several other genera.

Silicified remains of cycads and coniferous trees occur in the Dirt-beds, and some, at least, are in the position of growth.

The Purbeck series in its typical development is exposed in the south of Dorsetshire and in the Vale of Wardour. Farther north, owing to the overlap of the Cretaceous, only the lower beds are seen. At

Swindon, as well as near Oxford and Aylesbury, they consist of fresh-water marls and limestones.

The upper part of the Purbeckian series is also exposed in the middle of the Wealden anticline in a band which runs from near Heathfield to the north of Battle. It consists chiefly of shales and limestones, with some bands of hard calcareous sandstone and of gypsum. These beds pass up conformably into the Wealden series. In the sub-Wealden boring near Battle the thickness of the gypsum deposits was very considerable.

CHAPTER XXVI

THE CRETACEOUS SYSTEM

THE Cretaceous beds (Fig. 122) form a broad band extending in an open curve from Flamborough Head to the Dorset coast, and, like the Jurassic beds, they have in general an easterly or south-easterly dip. But in the south of England the structure is complicated by a series of folds and faults which run from west to east. In consequence of these a broad arm of Cretaceous rocks spreads from the main band at Salisbury Plain to the shores of Sussex and Kent, and a narrower strip forms the southern rim of the Hampshire basin in the Isle of Purbeck and the Isle of Wight. Cretaceous rocks are also brought to the surface at one or two places in the midst of the Tertiary beds, both in the London and the Hampshire basins.

Except where it is broken by the sea the main outcrop is practically continuous, and it is only in the south that there are neighbouring outliers of any considerable extent. But far away to the north-west, around the basaltic plateau of Antrim and beneath the lavas of Mull and Morvern, Cretaceous beds are again met with. They contain marine fossils, and prove that at one time the Cretaceous sea must have covered the greater part of the British Isles. Both in Ireland and in Scotland, however, much of the deposit is littoral in character, and some of the Scottish beds are estuarine.

In the main outcrop of the Cretaceous rocks the Chalk is always the dominant member of the system, and everywhere it forms an undulating plateau which terminates westward in a well-defined escarpment overlooking the Jurassic or Triassic plains, while eastward it sinks gradually beneath the Tertiary or later deposits. This escarpment is one of the most marked of the physical features of Eastern England. and is known under various names in different parts of the country. It forms the Yorkshire and Lincolnshire Wolds in the north, and the Gogmagog and Chiltern Hills farther to the south.

In the easterly arm the lower beds play a more important part than in the main outcrop. The hilly region in the middle of the Weald consists of Lower Cretaceous rocks; but the North Downs and the South Downs are formed by the Chalk.

The Cretaceous system falls naturally into two divisions, which differ widely in character and in distribution.

FIG. 122.—THE CRETACEOUS SYSTEM.

The Lower Cretaceous consists chiefly of sands and clays, in part of fresh-water origin and in part marine.

The Upper Cretaceous consists mainly of Chalk, but at its base is a variable series of clays and sands. Except in the west of Scotland, it is altogether marine.

It is not, however, the difference in lithological character that constitutes the principal reason for separating the Lower from the Upper Cretaceous, but rather the difference in their distribution. The Lower Cretaceous is comparatively limited in extent. It is fully developed in the Weald, the Isle of Wight and the Isle of Purbeck; but westward it is completely overlapped by the Upper Cretaceous, which here extends almost to the Carboniferous syncline of Devonshire. Towards the north, also, the overlap is almost equally marked, and throughout the greater part of the Cretaceous outcrop the Upper Cretaceous rests directly upon Jurassic rocks. The Lower Cretaceous, however, appears at intervals, but generally only the upper beds of that division. It is only in the north and south of England that the whole of the Lower Cretaceous is present.

In the distant exposures of Ireland and Scotland the Lower Cretaceous is altogether absent, and the Upper Cretaceous rests directly upon the older rocks.

In all directions, therefore, the Upper Cretaceous sea spreads far beyond the margins of the Lower Cretaceous waters. And this is true not only of the British Isles, but also of a large part of the globe. Nearly everywhere the Upper Cretaceous extends beyond the limits of the Lower. Almost everywhere about this period the sea overflowed the shores of the ancient continents, and the ocean grew at the expense of the land. The overflow appears to have taken place almost simultaneously throughout the globe, and it is one of the most striking and widespread events in geological history. It is often called the 'Cenomanian transgression,' but the transgression or overflow began before the Cenomanian epoch.

In England the most remarkable of the Cretaceous deposits are the Greensands and the Chalk. Greensand is not by any means confined to this system. Chalky beds are also met with elsewhere, but in no other system do they approach in extent or thickness the Chalk of the Cretaceous.

The Greensands always owe their colour to the presence of grains of glauconite, but they vary considerably in composition and structure. One variety, known in England as malmstone and in France as gaize, consists principally of colloid silica with only a small proportion of grains of quartz and a very variable amount of glauconite. Other varieties are true sandstones, made of grains of quartz and glauconite and flakes of mica, generally with a more or less calcareous cement. Still other beds are formed so largely of sponge spicules that they are really organic deposits rather than clastic sediments.

At the present day glauconite may be formed at any depth down to 2,000 fathoms, or even beyond. Where the amount of terrigenous material is great, the proportion of glauconite is small; and the deposits in which the quantity of glauconite is sufficient to give a green colour to the whole occur mostly about the limit of wave and current action, especially at depths of 200 or 300 fathoms.

To the unaided eye the Chalk differs from other calcareous rocks in the purity of its colour, the absence of any visible crystalline structure and the extreme fineness of the particles which compose it. Chemically it is distinguished by the very small proportion of insoluble material which it contains. Frequently the residue which remains after treatment with hydrochloric acid amounts to less than 2 per cent. But in the more marly beds it may rise to 15 or 20 per cent. Towards the base the quantity increases, but it becomes obvious even to the eye that the Chalk is no longer pure. The insoluble residue consists chiefly of detrital material derived from the land; and in the south of England it is noticeable that the proportion increases gradually from Kent to Dorset.

Microscopically, the Chalk consists chiefly of the tests of foraminifera, minute fragments of shells, especially of *Inoceramus*, and a matrix of very finely divided calcareous material. The proportion of these constituents varies greatly. In some cases the foraminifera or the fragments of shells predominate, but in general the finer matrix forms the bulk of the rock. Sponge spicules are sometimes very numerous, and sometimes little globules of colloid silica abound. Often small round calcareous discs are common in the matrix, and these were formerly supposed to be of the same nature as the coccoliths of the *Globigerina* ooze, but they do not show the characteristic stud-like form.

In the presence of *Globigerina* and other foraminifera, and the very fine texture of the whole deposit, the Chalk undoubtedly resembles the *Globigerina* ooze of the present ocean-floors; and accordingly many writers have concluded that it was laid down in deep waters. The abundance of hexactinellid sponges, similar to those which now live at considerable depths, adds support to this view. Many of the fishes, moreover, possess the delicate skeletons and slender fin-rays characteristic of deep-sea forms.

The Mollusca, on the other hand, point to a different conclusion. Deep-sea gastropods and lamellibranchs generally possess thin and fragile shells, while the shells which are found in the Chalk are often thick and strong like those of shallow-water molluscs. Moreover, many of the genera which are common in the Chalk are now characteristic of shallow water rather than of the deep sea.

It has also been remarked that the *Globigerina* ooze seldom contains so high a proportion of carbonate of lime as most of the English Chalk, and the residue insoluble in acid is almost always considerably greater. It has even been suggested that the Chalk is similar in origin to the fine calcareous mud which is formed by the waste of coral reefs, but the almost total absence of corals or of coral fragments seems to negative this hypothesis.

No doubt the depth of the water varied from time to time. In some of the marly and nodular beds gastropods are very abundant, indicating a comparatively shallow sea; but generally they are rare. A study of the Mollusca of the bed known as the Chalk Rock has led to the conclusion that that deposit was formed at a depth not much exceeding 100 fathoms. But the Upper Chalk, with its abundant fauna of echinoids, was formed in a deeper sea.

At whatever depth the Chalk was formed, it was certainly laid down in a sea which was remarkably free from detrital material. Either the water was very deep, or the shore was far away, or the rivers brought but little sediment from the land.

It was, moreover, a sea of great extent, for the Upper Chalk spreads with little change of character from England to the east of Russia. But its width was comparatively small. In Scotland the deposits of the Chalk period are in part estuarine; in Saxony they consist chiefly of sandstone. The northern border of the sea seems to have stretched from Scotland to the south of Scandinavia; the southern border lay north of the Alps. The Chalk sea was therefore hardly comparable with the great oceans, but rather with the present Mediterranean.

Fauna and Flora.—So far as our islands are concerned, the flora of the Cretaceous is practically the flora of the fresh-water deposits at its base, for elsewhere remains of plants are rare. The forms which are found in these lower beds are very closely related to those of the Jurassic rocks. Ferns and cycads are still the dominant groups. Conifers, Equisetaceæ and a few other forms also occur. On the Continent Dicotyledons appear in the Upper Cretaceous.

The fauna of the Cretaceous period includes many of the genera which lived during Jurassic times, but it differs in many important respects. The difference is greatest in the case of the Chalk, partly, no doubt, because in point of time the Chalk is farthest removed from the Jurassic deposits; but partly also because it was laid down under very different conditions.

Sponges are more abundant than in any other system. Calcareous forms are common in the Lower Greensand, the highest division of the Lower Cretaceous. In the Upper Cretaceous, siliceous forms predominate, especially in the Chalk; but calcareous forms are occasionally common in the Upper Greensand.

In the British Cretaceous, corals are nowhere abundant, and they form no reefs or beds comparable with those of the Middle Jurassic. A few simple corals, however, occur, such as *Trochocyathus*, *Parasmilia* and *Micrabacia*, and one or two compound forms such as *Holocystis*.

Echinoderms, on the other hand, are very common, especially in the Chalk. Echinoids predominate, and, indeed, this class attains its greatest development in the Upper Cretaceous. Amongst the most important genera are *Galerites*, *Micraster*, *Holaster* and *Echinocorys*. The crinoids are represented by *Marsupites* and a few other forms. Star-fish also occur.

Brachiopods are not so numerous as in the Jurassic deposits. But *Terebratula* and *Rhynchonella* are still common, and other genera are also met with.

Polyzoa are often found, both cyclostomatous and cheilostomatous forms being abundant.

The Lamellibranchia are well represented. Fresh-water forms such as *Unio* and *Cyrena* occur in the Lower Cretaceous; but the special characteristic of the period is the abundance of *Inoceramus*, and (in Southern Europe) of the remarkable genus *Hippurites* and its allies. *Gervillia* and *Spondylus* are other genera which may be mentioned.

Gastropods are common in some beds. Amongst them are the marine genera *Pleurotomaria* and *Aporrhais* and the fresh-water form *Viviparus*.

Cephalopods are very abundant, especially ammonites and belemnites. The latter include the genus *Belemnites* itself, and also *Actinocamax* and *Belemnitella*. Amongst the ammonites are many of the normal type, but there is also a large variety of uncoiled or partly uncoiled forms such as *Hamites*, *Baculites*, *Scaphites*.

Fish remains are common, and the teeth of *Ptychodus* are well-known fossils from the Chalk. Reptiles are also found, *Iguanodon* being one of the most striking forms; the other groups of reptiles resemble those of the Jurassic system. A single genus of birds, *Enaliornis*, has been found in England; and other genera occur abroad. Many of them retain certain reptilian characters, such as the presence of teeth set in sockets. No mammalia are known in the English Cretaceous.

A.—LOWER CRETACEOUS

In the south of England the Lower Cretaceous passes downwards without a break into the Jurassic and upwards into the Gault. The lower part is of fresh-water origin and is called the Wealden, the upper part is marine and is known as the Lower Greensand. Towards the north the higher beds overlap the lower, and consequently in the Vale of Wardour only the top of the Wealden series is present, and still farther to the north the Lower Greensand rests directly and unconformably upon the Jurassic.

In Yorkshire and Lincolnshire both the Wealden and the Lower Greensand are represented by marine deposits; but again the higher beds overlap the lower—in this case towards the south—and accordingly in Norfolk the lower beds are absent, and south of Ely the Lower Greensand rests directly upon the Jurassic.

Thus it appears that in the early part of the period the central district was land, separating a northern sea from a southern lagoon or estuary. Gradually the waters rose, and the deposits spread farther and farther over the central land until, in Lower Greensand times, the whole area was invaded by the sea. Even then, however, there remained a considerable difference between the fauna and deposits of the north and those of the south.

According to the manner in which the Lower Cretaceous was laid down, England may therefore be divided into three districts: (1) a southern district, in which the Wealden series consists of fresh-water deposits; (2) a central district, in which the Wealden is altogether absent; and (3) a northern district, in which the Wealden is represented by marine deposits.

Owing to the overlap of the Upper Cretaceous, the boundaries of these three areas cannot be determined with precision. But the southern district extends as far north as the Vale of Wardour, where the last exposures of the Wealden fresh-water beds are seen;[1] the central district stretches from Devizes to Ely; and the northern district includes Norfolk, Lincolnshire, and Yorkshire.

Southern District

In the south of England the Lower Cretaceous forms the central portion of the dome of the Weald, occupying almost the whole of the area between the North and South Downs (Fig. 123). Another anticlinal fold brings it again to the surface in the Isle of Wight, of which it forms the southern half; and owing to the same fold it crops out in a narrow band which runs from east to west across the Isle of Purbeck. A few small inliers occur along another anticlinal axis which passes about six miles north of Weymouth. Both towards the west and towards the north it is overlapped by the Upper Cretaceous; but it reappears in the Vale of Wardour, where the Chalk escarpment has been cut back far to the east of its general direction. Here, however, the outcrop is narrow, and but little of the fresh-water series is visible.

[1] Unless the Shotover Sand (for which see the account of the Central District) belong to the Wealden series.

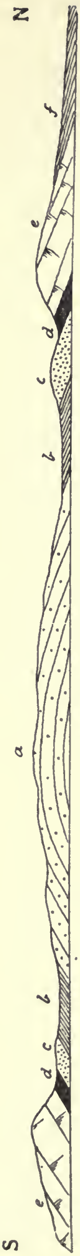


Fig. 123.—Diagrammatic Section across the Weald.

a, Hastings Sand; *b*, Weald Clay; *c*, Lower Greensand; *d*, Gault and Upper Greensand; *e*, Chalk; *f*, Tertiary.

Throughout this district the Wealden series is represented by fresh-water deposits, and the Lower Greensand is marine. In the Weald both series thicken from east to west; but they appear to attain their maximum about the longitude of the Isle of Wight, and in Dorsetshire they begin to thin in a westerly direction.

In the Isle of Wight the base is not visible, but in the Weald and the Isle of Purbeck the Wealden passes without the slightest break into the Purbeck beds below, and the boundary between the two series is purely artificial. Similarly, there is no very sharp line between the Lower Greensand and the Gault above. But the boundary between the Wealden and the Greensand is always clear and well defined, and is often marked by a line of pebbles or of coarse grit. There is, however, no proof of unconformity, and the boundary is such as might be expected if the sea invaded an area which was already covered by fresh water.

In the Vale of Wardour, which lies near the margin of the old lagoon, the lower part of the Wealden series is absent and the upper beds rest unconformably upon the Purbeck.

The Weald is the largest area of Lower Cretaceous rocks in England, and may accordingly be taken as the type of the southern development. The subdivisions which have there been recognised are as follows:—

Lower Greensand		Folkestone beds. Sandgate beds. Hythe beds. Atherfield Clay.
Wealden	Weald Clay.	
	Hastings Sand	Tunbridge Wells Sand. Wadhurst Clay. Ashdown Sand.

The subdivisions in the first and second columns can generally be recognised over the whole of the southern district; the minor subdivisions in the third column cannot be clearly distinguished except in the Weald.

Wealden Series.—The Hastings Sand forms the hilly ground in the middle of the Weald, rising at

Crowborough Beacon to a height of nearly 800 feet. It consists chiefly of light-coloured sands or soft sandstone with variable and subordinate bands of clay. But towards the middle there is a very constant bed of clay, 100 to 150 feet in thickness, which is called the Wadhurst Clay, and which separates the Ashdown Sand below from the Tunbridge Wells Sand above. Close to the base of the Wadhurst Clay there are nodules and bands of iron-stone, which in early days were the principal source of iron in Great Britain. In some parts of the Weald other beds of clay attain a considerable thickness. Near Hastings and Fairlight, for example, the lower part of the Wealden becomes so argillaceous that it is often separated as a special subdivision under the name of the Fairlight Clays; but the Fairlight Clays are contemporaneous with the lower part of the Ashdown Sand of other districts.

As a rule fossils are not common in the sandy beds, but remains of plants and reptiles occur. The Fairlight Clays have yielded a large number of plants. The Wadhurst Clay is very fossiliferous. *Viviparus fluviorum* and *Cyrena media* are here the principal shells. *Lepidotus mantelli* and other fish, *Iguanodon* and other reptiles, are also abundant.

The Weald Clay forms the broad depression which surrounds the central hilly region of the Weald and separates it from the Downs. It consists chiefly of brown, blue or yellow clay, but includes layers of shelly limestone which are often hard enough to take a good polish and are known under various local names, such as the 'Bethersden marble.' There are also occasional beds of sandstone. *Viviparus fluviorum* and *Viviparus sussexensis* are the commonest shells, but fresh-water lamellibranchs such as *Unio* and *Cyrena* also occur, and small ostracod crustaceans such as *Cypridea* are often very abundant. Remains of reptiles and plants are also found in the clay.

When traced from the Weald towards the west, the Wealden series shows certain changes. In the Isle of Wight the Hastings Sand does not reach the surface; but the Weald Clay is fairly exposed in the northern part of Sandown Bay on the eastern coast, and on the western coast is well exhibited in the cliffs between Compton Bay and Atherfield. A striking feature is the 'pine-raft' near Brook Chine. This is a collection of coniferous trunks which were evidently washed down into the Wealden delta and there became water-logged and sank.

In the Isle of Purbeck the whole of the Wealden series is exposed to view. It thins towards the west, and as it thins the sediment grows coarser, the clays giving place to sands, and the sands to pebbly grits. Three small inliers lie to the north of Weymouth, the most westerly being that of Ridgeway.

Lower Greensand.—The Lower Greensand is harder than the Weald Clay below and the Gault above, and consequently it forms a prominent ridge in front of the main escarpment of the Downs, including the heights of Hindhead, Leith Hill, &c.

It is a variable series of sands and clays, often, but by no means always, full of glauconitic grains. Some of the beds are highly calcareous, and under the name of 'Kentish Rag' are used for building and are burnt for lime.

The subdivisions which have been recognised in the Weald may be briefly described as follows :—

4. Folkestone beds .	Chiefly sandy, sometimes with hard cherty beds made up largely of sponge spicules, sometimes with irregular layers of ironstone.
3. Sandgate beds .	Generally more or less argillaceous, but with a good deal of sand and sandy clay. Fuller's earth occurs in some districts.
2. Hythe beds .	Sands and limestone. Includes most of the 'Kentish Rag.'
1. Atherfield beds .	Chiefly brown clay.

These divisions, however, are purely lithological and have no palæontological basis. They are therefore only of local value. The Atherfield Clay retains the same general character in the Isle of Wight and the Isle of Purbeck ; but the Sandgate beds cannot be definitely distinguished. In general, the Lower Greensand of the south of England may be divided into a lower argillaceous stage, the Atherfield Clay, and an upper arenaceous stage, including the rest of the series.

Amongst the more common and characteristic fossils of the Lower Greensand are *Peltastes Wrighti*, *Meyeria magna*, *Terebratula sella*, *Exogyra sinuata*, *Perna Mulleti*, *Gervillia sublanceolata*, *Ammonites Deshayesi*.

Central District

In the middle of England the Lower Greensand appears at intervals along the Cretaceous outcrop from Devizes to Ely ; but it rests directly and unconformably upon the Jurassic beds below, and there is no trace of the Wealden unless the Shotover Sands belong to that series. Its base is often pebbly, and in Bedfordshire and Cambridgeshire is frequently full of coprolites or phosphatic nodules, which were formerly extensively worked for manure. The greater part of the series consists of white, yellow or brown sands, sometimes with highly ferruginous beds, sometimes with beds of clay ; but it is not possible to distinguish the subdivisions which have been recognised in the south of England. Near Faringdon, in Berkshire, is a remarkable deposit of gravel which is formed very largely of sponges.

On Shotover Hill, near Oxford, and at several other places between Oxford and Aylesbury, there are outliers of ferruginous sand containing *Viviparus sussexensis* and other fresh-water shells, and resting unconformably upon the Jurassic beds. The evidence of their age is not conclusive, but in one or two places they are associated with beds containing marine Lower Greensand fossils, and they are believed to be a fresh-water facies of the Lower Greensand.

Northern District

The Lower Cretaceous of Yorkshire and Lincolnshire differs so much from that of Southern England that no exact correlation of the strata is yet possible. Palæontologically, indeed, these northern deposits are much more closely connected with those of Russia. They contain many species which are found in that country, but are unknown in the south of England and in France. Apparently the sea which covered Northern Russia extended into the north-east of England. When, however, the land area of Central England and the fresh waters of the Weald were invaded by the sea, it was not the fauna of the northern sea which crept over the area, but the fauna of a sea which lay to the south of England, and many of these southern forms spread for a time into the waters of the northern sea.

It is in the neighbourhood of Speeton, north of Flamborough Head, that the most definite palæontological sequence has been made out; and consequently the Speeton beds may be taken as the type of the northern development.

The deposits here consist almost entirely of clay or shale, which is for the most part dark in colour. They rest directly upon the Kimeridge Clay without any evident sign of erosion. Belemnites are by far the most abundant and characteristic fossils, but ammonites and other forms occur. One band has yielded a considerable number of the sea-urchin *Echinospatagus cordiformis*. By means of the Belemnites the whole series may be divided as follows:—

5. Zone of *Belemnites minimus* (base of Upper Cretaceous).
4. ,, ,, *brunsvicensis*.
3. ,, ,, *jaculum*.
2. ,, ,, *lateralis*.
1. Coprolite bed.

The coprolite bed is a thin seam of black phosphatised nodules, only about four inches thick. It contains fossils which have been found in Russia in beds that have been referred to the Portlandian. *Belemnites lateralis* is a short, thick species which is common also in Russia. It is rare in the south, but one or two specimens have been found in the Portlandian of Boulogne. *B. jaculum* is a long and slender form which occurs in France, Germany and the Alps. *B. brunsvicensis* is believed to be a descendant from some form allied to *B. lateralis*, and is found in Russia and Germany, but not in the southern Cretaceous. On the whole, the fauna of the *B. lateralis* zone is very distinct from that of the south, while the faunas of the two succeeding zones show a mixture of northern and southern forms.

Because the Speeton Clays are marine and the corresponding beds of Southern England are in part of fresh-water origin, direct comparison is very difficult. *Belemnites minimus* is a common Gault fossil, and the zone of *Belemnites minimus* probably represents the base of the Upper Cretaceous. The zone of *Belemnites brunsvicensis* contains *Ammonites Deshayesi* and other fossils which show that it represents in part the Lower Greensand, but it is quite possible that the *B. jaculum* zone may also belong in part to that series. There is no very evident gap between the Speeton series and the Kimeridge Clay below, and it appears therefore that the former must represent the whole of the beds from the top of the Kimeridgian to the base of the Upper Cretaceous. But the seam of phosphatic nodules at its base probably indicates a pause in deposition, and the duration of the pause is unknown.

The Speeton Clay is overlapped to the west and south by the Upper Cretaceous; but Lower Cretaceous beds reappear in Lincolnshire. Here they are formed of coarser sediments than at Speeton, and include beds of sandstone and limestone. The limestone is sometimes partly replaced by ironstone. The same zones can be recognised as in Yorkshire, and the deposits were evidently laid down in the same sea, but nearer to its southern margin. The following divisions are recognised :—

Carstone . . .	(in part)	=	Zone of *B. minimus* (Upper Cretaceous).
Tealby Limestone and Roach Ironstone	. .	=	„ *B. brunsvicensis*.
Tealby Clay	. .	=	„ *B. jaculum*.
Claxby Ironstone Spilsby Sandstone	. .	=	„ *B. lateralis*.

At the base of the Spilsby Sandstone is a bed of phosphatic nodules. Several Lower Greensand forms, such as *Exogyra sinuata* and *Perna Mulleti*, have been recorded from the Tealby Clay, and several occur also in the Tealby Limestone. The Carstone is a pebbly ferruginous sand or sandstone containing very few fossils except at the top, where the Gault species *B. minimus* and *Terebratula biplicata* are found. One or two Lower Greensand species occur at the base, where phosphatic nodules are also found. Possibly they may have been derived from the destruction of an older stratum.

APPROXIMATE CORRELATION OF THE LOWER CRETACEOUS DEPOSITS

Southern District	Central District	Norfolk	Lincolnshire	Yorkshire	
Lower Greensand	Lower Greensand	Carstone (in part) Snettisham Clay	Carstone (in part) Tealby Limestone and Roach Ironstone	Zone of *Belemnites brunsvicensis*	Speeton Clay
Wealden Series		Sandringham Sand	Tealby Clay	Zone of *Belemnites jaculum*	
			Claxby Ironstone Spilsby Sandstone	Zone of *Belemnites lateralis*	

The Carstone extends across the Wash into Norfolk, where it is well exposed in the cliffs of Hunstanton. South of Hunstanton it is underlaid by the Snettisham Clay, which contains *B. brunsvicensis ;* and beneath this is a series of light-coloured sands, known as the Sandringham Sands. These sands, however, have not yet yielded any recognisable fossils, and neither the zone of *B. jaculum* nor that of *B. lateralis* has been proved to exist south of Lincolnshire.

B.—UPPER CRETACEOUS

The Upper Cretaceous is much more uniform than the Lower. It was laid down in a deeper and a wider sea. Lithologically, it may generally be divided into calcareous series above, and an argillaceous and arenaceous series below. The former is the Chalk, the latter is known as the Gault and Upper Greensand. The Chalk itself is some, times marly and sometimes contains glauconitic grains, especially towards its base, so that in many localities a ' Chalk Marl ' and a ' Chloritic Marl ' have been distinguished. Other beds are hard and have also received special names. But these lithological divisions are not universally recognisable ; and it is now usual to adopt a palæontological classification. The whole of the Upper Cretaceous is divided into a number of zones, which are grouped as follows :—

Upper Chalk	Zone of *Ostrea lunata*	Senonian.
	,, *Belemnitella mucronata*	
	,, *Actinocamax quadratus*	
	,, *Marsupites testudinarius*	
	,, *Micraster cor-anguinum*	
	,, ,, *cor-testudinarium*	
Middle Chalk	,, *Holaster planus*	Turonian.
	,, *Terebratulina lata*	
	,, *Rhynchonella Cuvieri*	
Lower Chalk	,, *Holaster subglobosus*	Cenomanian.
	,, *Ammonites varians*	
Upper Greensand and Gault	,, *Pecten asper*	Albian.
	,, *Ammonites rostratus*	
	,, ,, *lautus*	
	,, ,, *interruptus*	
	,, ,, *mammillatus*	

Still higher beds appear upon the Continent and are known as Danian.

The names in the left-hand column are based on the lithological nature of the beds in England. Those in the right-hand column are of French origin and have no lithological significance. They are intended for universal application, and can be used even when the character of the deposits is entirely different, provided that the correlation of the strata can be determined palæontologically.

The *Holaster planus* zone is included by the Geological Survey in the Upper Chalk. Many writers place it in the Middle Chalk, and this arrangement has the advantage of bringing our terminology more nearly into line with the French.

Besides the zone fossils, the Gault and Upper Greensand include many other characteristic forms. Amongst the commonest are *Terebratula biplicata, Inoceramus sulcatus, I. concentricus* and *Belemnites minimus*.

The Chalk also contains a very large number of well-known species, such as *Siphonia Könige, Galerites conicus, Echinocorys* (*Ananchytes*) *vulgaris, Spondylus spinosus, Inoceramus mytiloides*.

There is no longer the marked difference between the deposits of the south and of the north of England that existed in Lower Cretaceous times, for both areas were covered by the same sea. But still a difference remains, especially in the lower beds. The Gault and Upper Greensand of the south are represented farther north by a thin bed of red chalk, which lies beneath the ordinary white chalk.

Accordingly England may still be divided into a northern and a southern district; and for convenience of description a central district may also be distinguished.

Southern District

This area may be taken to include the whole of England south of the Thames, but it cannot be sharply separated from the Central District.

Gault and Upper Greensand.—The Albian of Continental writers is represented by the Gault, sometimes with and sometimes without the Upper Greensand above. Palæontologically, the topmost part of the Lower Greensand should be included, for it is here that the change of fauna begins.

No line can be drawn between the Upper Greensand and the Gault, for the former is only a sandy facies of the latter, and the beds which are sandy in one locality are represented by clay in others. The series is divided into five zones, in descending order —

5.	Zone of *Pecten asper*			Sand.
4.	,,	*Ammonites*	*rostratus*	Clay or sand.
3.	,,	,,	*lautus*	Clay.
2.	,,	,,	*interruptus*	Clay.
1.	,,	,,	*mammillatus*	Sand

The first of these zones is always sandy, and is usually included in the Lower Greensand, which it resembles lithologically.

The next two zones always consist of clay. The zone of *Ammonites rostratus* is sometimes sandy and sometimes clayey; and the zone of *Pecten asper*, when it is present, is always formed of sand. The clay is called the Gault and the sand is called the Upper Greensand.

At Folkestone no Upper Greensand is present, and the Chalk rests directly on the Gault. It is only in the extreme west of Kent, near the village of Westerham, that the Upper Greensand begins to appear. Through Hampshire and the Isle of Wight the sandy facies spreads downwards, and in Dorsetshire the whole of the two upper zones is formed of sandy beds. Still farther west the series passes over the Jurassic and older rocks, and the higher beds overlap the lower, so that in West Dorset and in Devon the sandy beds representing the zones of *Ammonites rostratus* and *Pecten asper* rest directly upon the older rocks, without any bed of clay beneath.

The Chalk.—The Gault and Upper Greensand are followed by the Chalk, which forms the North and South Downs, Salisbury Plain and its south-westerly continuation, and also the axes of the Isle of Wight and the Isle of Purbeck.

The Chalk is by no means constant either in composition or texture, but the general appearance of the deposit is remarkably uniform, and the lithological variations are far from conspicuous to the eye. Often, indeed, no trace of bedding is visible, and often the stratification is revealed only by lines of flints. But careful examination shows that sometimes the Chalk is soft and marly, sometimes it is hard and lumpy; sometimes it contains numerous rows of flints, sometimes few or none. Seams of phosphatic nodules occur at certain horizons, and grains of glauconite are abundant at others.

It is accordingly possible to distinguish definite lithological subdivisions, and some of these are remarkably constant in character over wide areas. In the south of England the following divisions can usually be recognised :—

		Zones.
Upper Chalk	White chalk, usually with many flints; more or less nodular towards the base	*Belemnitella mucronata* to *Holaster planus.*
Middle Chalk	Soft white chalk, with occasional beds of marl, usually with few flints	*Terebratulina lata.*
	Hard nodular chalk, Melbourn Rock	*Rhynchonella Cuvieri.*
Lower Chalk	Thin bed of marl (Belemnite Marl)	*Holaster subglobosus.*
	Massive white chalk	
	Grey chalk	*Ammonites varians.*
	Chalk marl, with chloritic marl at base	

The lithological divisions do not always correspond precisely with the zones.

The base is usually glauconitic and often sandy, and is commonly distinguished by the name of Chloritic Marl. This is followed by soft grey marly chalk, graduating upwards into a more solid chalk which is still grey in colour. These subdivisions together constitute the zone of *Ammonites varians.*

The grey chalk is succeeded by massive white chalk, with *Holaster subglobosus,* &c., and at the top of this is a thin but very constant band of soft marl containing *Actinocamax plenus* in abundance. This marl is often known as the Belemnite Marl or the sub-zone of *Actinocamax plenus.* It forms the upper limit of the Lower Chalk.

The Middle Chalk begins with a hard nodular band, called the Melbourn Rock, and this is followed by a soft white chalk with occasional beds of marl and usually with few flints. The Melbourn Rock and a part of the softer chalk above belong to the *Rhynchonella Cuvieri* zone; the rest of the Middle Chalk to the zone of *Terebratulina lata.*

The Upper Chalk is usually white and pure, but seams of marl occur in places, and nodular and lumpy beds are often found towards the base. In the south of England it is usually distinguished by the abundance of flints. Formerly, in fact, it was called the Chalk with Flints, and the Lower and Middle divisions were known as the Chalk without Flints; but this distinction cannot be maintained. The *Marsupites* zone contains comparatively few flints, while towards the west flints become abundant in the Middle Chalk. Palæontologically, the Upper Chalk is characterised by the great abundance of *Micrasters* in the lower zones, and of belemnites (*Belemnitella* and *Actinocamax*) towards the top.

Towards the west the character of the Chalk gradually changes. In Devonshire the lower part becomes a calcareous sandstone overlaid by a bed of hard quartziferous limestone. It was evidently deposited upon the margin of the Cretaceous sea. The Middle Chalk is hard and gritty at its base, while higher up it is a chalk with many flints. On this account it was formerly referred to the Upper Chalk, but the fossils are those of the *Terebratulina lata* zone. The true Upper Chalk includes the zones of *Holaster planus* and *Micraster cor-testudinarium,* and retains its chalky character. The higher zones have been removed by denudation.

Central District

The Central District may be considered to extend as far north as the south of Norfolk.

Gault and Upper Greensand.—The Albian retains the same general characters as in the south of England. About Devizes and the Vale of Pewsey the Upper Greensand is well developed and forms the zones of *Pecten asper* and *Ammonites rostratus*. But towards the north the sandy beds are gradually replaced by clay, and the Upper Greensand finally disappears in Bedfordshire. In Cambridgeshire the upper part of the Gault was eroded before the deposition of the Chalk. Its upper surface is accordingly uneven, and the *Ammonites rostratus* zone in some places appears to have been completely worn away. The erosion was due, not to elevation above the surface of the water, but rather to the action of currents upon the floor of the sea.

The Chalk.—The Chalk of the Central District may be divided as follows :—

Lithological Divisions.		Zones.
Upper Chalk	Chalk with many flints	*Micraster* zones.
	Chalk Rock	*Holaster planus.*
Middle Chalk	Chalk with few flints	*Terebratulina lata.*
	Melbourn Rock	*Rhynchonella Cuvieri.*
Lower Chalk	Belemnite Marl Chalk without flints Totternhoe Stone	*Holaster subglobosus.*
	Chalk Marl (with Cambridge Greensand at its base)	*Ammonites varians.*

The lithological divisions do not correspond exactly with the zones.

As in the south of England, the *Ammonites varians* zone consists chiefly of marly chalk, and is known as the Chalk Marl. In Bedfordshire and Cambridgeshire it rests upon an eroded surface of the Gault, and at its base is a sandy or pebbly bed containing coprolites and including many phosphatised Gault fossils. This deposit is commonly known as the Cambridge Greensand ; but it is a part of the Chalk Marl, and the Gault fossils which it contains have been washed out from the upper part of that formation.

The remainder of the series consists chiefly of normal chalk ; but it is divided by three bands of harder chalk, which can be traced over most of the area, and serve as convenient guides in delimiting the principal subdivisions.

The lowest of these hard bands is the Totternhoe Stone, which rests upon the Chalk Marl and forms the base of the *Holaster subglobosus* zone ; the second is the Melbourn Rock at the bottom of the Middle Chalk ; and the third is the Chalk Rock, which lies at the base of the Upper Chalk.

Over most of the Central District the whole of the Chalk above the *Micraster* zones has been removed by denudation. But higher beds appear to be present at Taplow, near Maidenhead, and at Needham Market, in Suffolk.

Northern District

The Northern District extends from the north of Norfolk to Flamborough Head.

In spite of minor changes, the general character of the Chalk remains unaltered; but no Gault or Upper Greensand appears below it. The place of these deposits is taken by a bed of red chalk, which is a conspicuous feature in the cliffs of Hunstanton.

Red Chalk.—The change in the character of the Albian begins on the eastern border of the Wash. Gault of the southern type can be traced to King's Lynn; but beyond this point it rapidly thins, becomes marly in character and reddish in colour, and gradually passes into the Red Chalk. At Hunstanton the Red Chalk is about three feet thick and contains *Belemnites minimus*, *Terebratula biplicata*, *Inoceramus sulcatus*, *I. concentricus*, *Ammonites interruptus*, *A. rostratus* and other fossils characteristic of the Gault.

The Red Chalk continues through Lincolnshire, where it sometimes attains a thickness of ten or twelve feet, and into Yorkshire. But at the northern end of the Cretaceous outcrop near Speeton, the series thickens and

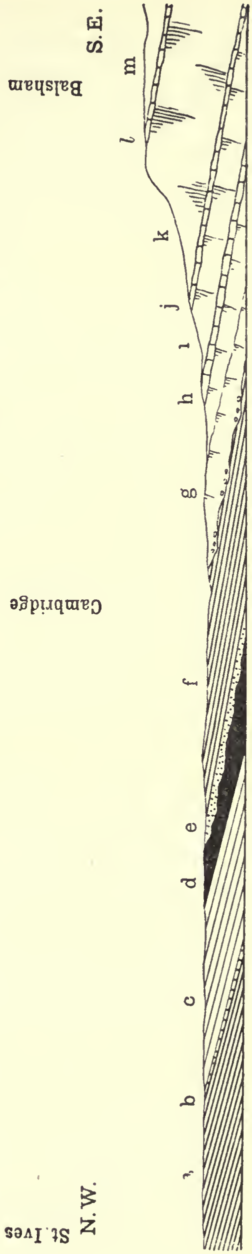


Fig. 124.—Diagrammatic Section from St. Ives through Cambridge to Balsham.

a, Oxford Clay; *b*, Elsworth Rock; *c*, Ampthill Clay; *d*, Kimeridge Clay; *e*, Lower Greensand; *f*, Gault; *g*, Chalk Marl with Cambridge Greensand at base; *h*, Totternhoe Stone; *i*, Lower Chalk; *j*, Melbourn Rock; *k*, Middle Chalk; *l*, Chalk Rock; *m*, Upper Chalk.

consists of marls and clays, for the most part red in colour, besides irregular beds of red marly chalk.

The Chalk.—The Lower Chalk is generally thinner than in the south, and it is no longer argillaceous towards its base. There is, in fact, no true Chalk Marl, and the *Ammonites varians* zone consists of hard white or grey chalk. The Totternhoe Stone is only about two feet thick, but may still be traced throughout the region. The Belemnite marls at the top of the Lower Chalk are present in Lincolnshire and Yorkshire. In some places the Lower Chalk includes red and purple bands.

The Middle Chalk is also thin, and unlike the corresponding beds of Central and South-eastern England, it often contains many lines of flints. The Melbourn Rock ceases to be distinguishable in Lincolnshire; but in Yorkshire practically the whole of the Middle Chalk is hard.

In contrast with the lower and middle divisions the Upper Chalk of the northern district appears to be considerably thicker than in the south of England. In Norfolk it is estimated to attain a thickness of more than 1,100 feet, and it includes higher beds than any which are known elsewhere in England. These topmost beds form the zone of *Ostrea lunata*, and are found only at Trimingham, east of Cromer.

In Lincolnshire the Chalk above the *Micraster* zones has been denuded. But in Yorkshire the *Marsupites* and *Actinocamax quadratus* zones reappear, and are both entirely destitute of flints.

Ireland

In the north-east of Ireland Cretaceous rocks appear at intervals around the borders of the basaltic plateau of Antrim, and bear witness to the extension of the Cretaceous sea in this direction. They rest unconformably upon Triassic and Liassic beds, and the nature of the deposits shows that they were laid down near the shore. Although they belong entirely to the Upper Cretaceous, they appear to form two distinct series separated by an unconformity.

The Lower series consists of marls and sandstones, glauconitic at the base and towards the top. They contain *Exogyra lævigata*, *Pecten asper*, *Ammonites varians*, &c., and appear to represent a part of the Lower Chalk of England, and perhaps the top of the Upper Greensand. It is possible, however, that owing to the sandy nature of the deposit some of the Upper Greensand forms may have survived into the period of the Lower Chalk.

The Upper series is formed chiefly of hard chalk, with rows of flints, and is generally glauconitic towards its base. In the eastern part of the area it passes downwards into glauconitic sands, not unlike those at the top of the lower series. But these sands contain *Echinocorys gibbus*, *Micraster* and *Galerites*, together with numerous fragments of *Inoceramus*, and clearly belong to the Upper Chalk. The chalk above appears to represent the Upper Chalk from the zone of *Micraster cor-anguinum* to the zone of *Belemnitella mucronata*. The greater part belongs to the latter zone.

Scotland

In Scotland Cretaceous rocks have been found in the island of Mull and on the adjacent peninsula of Morvern. As in Ireland, they owe their preservation to the protection afforded by the covering of Tertiary basalts; and like the Irish deposits, they belong entirely to the Upper Cretaceous, and show evidence of littoral or even estuarine conditions.

They rest unconformably upon the Jurassic and older rocks below, and have been divided into four groups—

4. Sands and marls with obscure plant-remains and one or two seams of lignite.
3. Chalk, sometimes silicified, glauconitic towards the base; with *Belemnitella mucronata*.
2. White sands, with a thin seam of lignite or coal.
1. Glauconitic sand, sometimes calcareous, sometimes argillaceous; with *Exogyra conica*, *Pecten orbicularis*, &c.

The lowest division evidently belongs to the Upper Greensand or the Lower Chalk; the third corresponds with the highest zone of the Chalk which is known in England, except at Trimingham. No unconformity is visible, but it is scarcely probable that the white sands which form the second division represent the whole of the intervening period.

The amount of carbonaceous material in the second and fourth divisions suggests that they are of estuarine origin. The latter may possibly be of Tertiary Age.

CHAPTER XXVII

THE EOCENE AND OLIGOCENE SERIES

Everywhere in Northern Europe the upper limit of the Chalk is marked by a sudden and striking change of fauna. Not only do species and genera disappear, but whole groups of animals die out and new types come in. In England the break is complete, and if we except such lowly forms as the Foraminifera, not a single species passes from the Cretaceous to the Tertiary. The change takes place at an unconformity, but an unconformity so slight that it is not visible in single sections. There is, however, no doubt that the uppermost beds of the Cretaceous were removed before the Tertiary deposits were laid down; and thus the change of fauna is in part explained. At a few localities in France, Belgium and Denmark, some of the missing beds are seen, and in these there is a certain mixture of Tertiary and Cretaceous species. But even here the gap is not by any means completely filled.

The change in fauna was not due entirely to lapse of time. It was in part the result of a complete alteration of conditions. Instead of the clear waters in which the Chalk was formed, there was now a muddy sea into which large rivers poured a vast amount of land-derived material. The ammonites, belemnites, and sea-urchins of the Chalk accordingly disappeared and their place was taken by shallow-water shells.

It is on account of this very abrupt change both in the fauna and in the character of the deposits that the line between the Mesozoic and Kainozoic rocks is placed at the top of the Chalk. But when we extend our view to other quarters of the globe, the boundary becomes less definite, and in some regions there appears to be a perfect passage from the one set of deposits to the other.

In England the Tertiary beds fall naturally into two groups separated by a considerable interval of time, and when they occur together, by a decided unconformity. But the unconformity is a local one, and in some parts of the Continent the succession is complete. The main divisions which are usually recognised are as follows:—

Upper Tertiary or Neogene	Pleistocene. Pliocene. Miocene.
Lower Tertiary or Palæogene . . .	Oligocene. Eocene.

The five smaller divisions are sometimes known as systems, but they are not comparable in magnitude with the systems of the Palæozoic and Mesozoic groups. Some writers recognise the Palæogene and Neogene as systems, and their subdivisions as series. But as, undoubtedly, the various systems and series of stratigraphy are of very unequal value, the question of terminology is of little importance.

The Miocene is absent in England and only a small part of the Oligocene is represented.

A.—THE EOCENE

The Eocene beds of England (Fig. 125) occupy two large triangular areas between the main Cretaceous outcrop and the easterly arm which forms the Weald. On the north of the arm lies the London Basin, and on the south the Hampshire Basin. Beyond the limits of these two great basins a number of small outliers rest upon the chalk of Salisbury Plain, the Chiltern Hills, &c., and seem to indicate that the Eocene deposits once covered the whole of South-eastern England. Moreover, the close similarity, in fauna and in lithological sequence, between the London and the Hampshire Basins shows that the same sea spread over both. The Eocene beds are themselves involved in the Wealden anticline, which must therefore be of post-Eocene date; and hence we may conclude that the London and Hampshire Basins were originally continuous, and owe their separation to the subsequent elevation and denudation of the Weald.

Although some of the Eocene outliers lie many miles from the two great basins, there is only one beyond the outcrop of the Chalk. This is the well-known Bovey Tracey deposit,[1] which rests unconformably upon the Palæozoic rocks of Devonshire. It is of fluviatile or estuarine origin, and there is accordingly no positive evidence that the Eocene sea spread westward of the present escarpment of the Chalk.

Throughout the south of England the Eocene consists of sands and clays, with pebble-beds and seams of lignite in some localities. Limestones are absent, and by far the greater part of the material is of terrigenous origin. The sea must have been shallow, and large

[1] Now believed to be of Oligocene age (see p. 452).

rivers brought full loads of sediment from the neighbouring land. In the east the deposits are entirely marine, but towards the west some

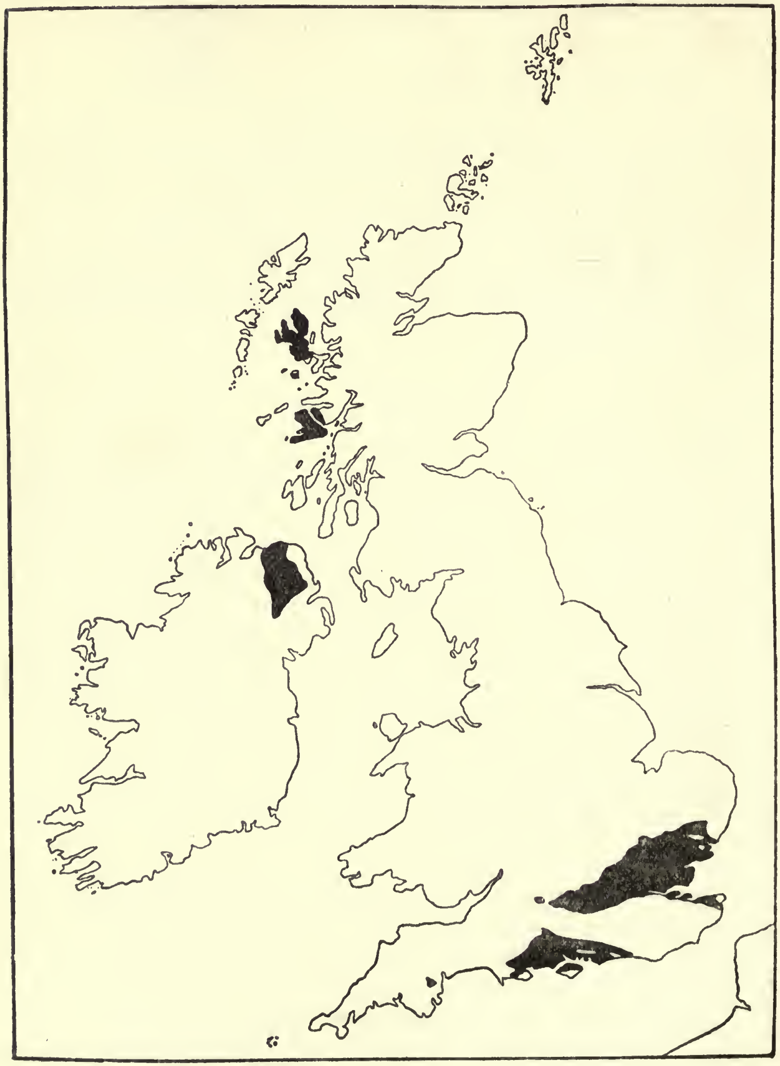


FIG. 125.—THE EOCENE AND OLIGOCENE SERIES.

of the beds contain brackish-water shells and remains of plants, and were evidently laid down in an estuary.

But while normal sedimentation proceeded quietly in the south of England, the north-west of the British Isles was a scene of extraordinary volcanic activity. A stupendous series of basaltic lava-flows overspread this region, and here and there great masses of plutonic rock were intruded. The horizontal lavas formed extensive plateaux, of which the remains may still be seen in Antrim, the Inner Hebrides and the west coast of the Scottish mainland. Intercalated between the basalt-flows are occasional lenticular patches of sedimentary deposits containing an Eocene flora.

Except in the Bovey Tracey outlier the Eocene beds of the south of England rest upon the Chalk, and generally without any visible unconformity. Often, indeed, the surface upon which they lie is very uneven and greatly eroded. But much of this erosion took place after the Eocene beds were laid down. At the base of the Eocene there is commonly a layer of unworn flints, similar in their irregular form to the flints of the chalk below. Evidently they were never rolled by rivers nor exposed to atmospheric weathering. But the Chalk has been dissolved by percolating water beneath the Eocene covering, and the insoluble flints were left behind.

Although the irregular surface of the Chalk cannot be taken as evidence of unconformity, and although no discordance is visible in single sections, an examination of a larger area shows that there must have been a considerable amount of denudation before the Tertiary beds were deposited. In Hampshire and the Isle of Wight the Eocene rests upon the *Belemnitella mucronata* zone, in Hertfordshire upon the *Micraster* zones. Even the *Belemnitella mucronata* zone is not the top of the Cretaceous system, and in England the highest zones were removed completely before the Tertiary beds were laid down.

Fauna and Flora.—In England the fauna of the Eocene is totally unlike the fauna of the Chalk, and the cause of the difference has already been discussed.

Because the sea was shallow and often muddy the fauna of the English Eocene consists for the most part of gastropods and lamellibranchs, but other groups are also represented.

Foraminifera are much less important than in the Chalk. *Nummulites*, however, is a characteristic genus which occurs in crowds in some of our English deposits. In the Mediterranean region and the south of Asia it forms massive beds of limestone.

Corals are generally rare. *Goniopora* (=*Litharæa*) *Websteri*, from the Bracklesham series, is one of the few forms which is found in any abundance.

Echinoderms, too, are seldom met with. *Schizaster* occurs in the Barton beds.

Brachiopods have entirely lost their former importance. *Lingula*, *Terebratula,* and one or two other genera still survive, but they are not common.

Gastropods and lamellibranchs, on the other hand, are very abundant. Amongst the gastropods the siphonostomatous forms predominate. *Fusus, Voluta, Conus, Pleurotoma,* are common in the marine beds; *Cerithium, Melania* and *Potamides* in the brackish-water deposits. The lamellibranchs include *Corbula, Cardita, Cardium, Chama,* &c.

Cephalopods are by no means common. The ammonites and belemnites are entirely extinct; but nautiloid forms such as *Nautilus* and *Aturia* are still met with. The Dibranchiata now become the dominant group; but their shells, whether external or internal, are not very readily preserved.

Decapod crustaceans are often found. Among the macrurous forms are *Hoploparia* and *Meyeria*; amongst the brachyurous forms, *Xanthopsis* and *Dromia.*

Vertebrates occur in considerable abundance in some localities. Sharks' teeth, such as *Lamna* and *Otodus,* are common, and remains of teleostean fishes are also found. Tortoises, turtles and crocodiles are the principal reptiles. Several genera of birds are also known. But the most striking feature of the period is the sudden appearance of numerous placental mammalia. These include carnivores, ungulates and lemuroids. A considerable number of species have been found in England; and many more in France, America, and elsewhere.

Remains of plants are very abundant in some beds, and they appear to indicate considerable changes of climate during the period. In the Reading beds, near the base of the system, are found *Laurus, Platanus,* &c., and the flora as a whole has a temperate aspect. In the London Clay and Bracklesham beds the characteristic forms are palms, figs, sequoias, &c., and the facies is that of a warm or even a tropical climate.

The London Basin

In the London Basin the Oligocene is entirely absent, and even the upper part of the Eocene has been removed by denudation; but the Lower Eocene is better developed than in the Hampshire Basin.

The beds are grouped as follows:—

Bagshot beds . .	Upper. Middle. Lower.
London Clay.	
Lower London Tertiaries	Blackheath and Oldhaven beds. Woolwich and Reading beds. Thanet Sands.

So far as the general nature of the deposits is concerned, the Eocene of the London Basin consists of three easily recognised divisions (Fig. 126). The lowest division is formed chiefly of sand, the middle division of clay; the upper division, like the lower, consists for the most part of sands. The first may be called the Lower London Tertiaries, the second is the London Clay, the third is the Bagshot series.

The Lower London Tertiaries form a narrow border around the basin, widening to the east of London into a fairly extensive but very irregular band. The London Clay fills the basin and covers by far the greater part of the area. Here and there, however, it is overlaid by the Bagshot beds, which form low hills or plateaux rising above the general level. Owing to their sandy character these elevated tracts are by nature barren and open heaths or commons. The largest lies to the north of Guildford and stretches twenty-four or twenty-five miles from east to west, and about twelve miles from north to south. It includes Aldershot Common, Ascot, Bisley, Bagshot Heath, &c. Nearer to London, Highgate Hill and Hampstead Heath are capped by the sands and gravels of the Bagshot series; many other outlying patches occur, especially in Essex.

The Lower London Tertiaries as a whole are thickest on the southern margin of the basin, especially in the east; and they thin towards the north.

The **Thanet Sands** are generally light-coloured sands, but towards the base they become argillaceous and full of glauconitic grains. Where they rest upon the chalk there is usually a layer of unworn green-coated flints. After the sands had been deposited, percolating water continued to dissolve the chalk beneath, and the flints were left behind. The green coating is probably due to the glauconite in the sands.

The Thanet Sands are well developed in the Isle of Thanet, but they thin towards the west

FIG. 126.—DIAGRAMMATIC SECTION ACROSS THE LONDON BASIN.
a, Chalk; *b*, Lower London Tertiaries; *c*, London Clay; *d*, Bagshot Beds.

and towards the north. The fossils which they contain are entirely marine, and are chiefly lamellibranchs and gastropods—for example, *Corbula regulbiensis* and *Aporrhais Sowerbyi.*

The **Woolwich and Reading Beds** are more variable. In the east of Kent the series consists throughout of light-coloured false-bedded sands containing marine fossils. In the western part of Kent and in East Surrey it is formed partly of sands, partly of grey clay, generally full of estuarine shells, sometimes with bands of oysters. Towards Reading it consists of mottled plastic clay and variegated sands, generally unfossiliferous, but sometimes with remains of plants. The Reading type occurs also along the northern margin of the basin, in Hertfordshire and Essex. Sometimes it includes a bed of pebbles cemented into a hard conglomerate known as the Hertfordshire pudding-stone.

Evidently during the deposition of this series the sea lay towards the east,the land towards the west. An estuary lay over East Surrey and West Kent, and probably the plant-bearing plastic clays are the fresh-water deposits laid down by the rivers which flowed into the estuary.

Amongst the marine fossils of this series are *Ostrea bellovacina, Cyprina Morrisi,* &c.; amongst the fresh-water and estuarine forms are *Unio, Cyrena, Viviparus.* Remains of fishes, reptiles, birds and mammals have also been found.

In the neighbourhood of London the sands of the Woolwich series are overlaid by a considerable thickness of current-bedded gravels which have sometimes been distinguished as a special subdivision under the name of the **Blackheath Pebble-Beds.** They consist chiefly of well-rounded flint-pebbles in a fine sandy matrix. The junction with the sands below is usually sharp and often very irregular, as if the surface of the sands had been eroded.

In the eastern part of Kent the place of these pebble-beds is taken by the **Oldhaven Beds,** which consist of fine drab-coloured sand, with a bed of flint-pebbles at the base.

Palæontologically neither the Blackheath nor the Oldhaven beds have any distinctive characters. Generally the fossils which they contain are much the same as those of the beds below, but sometimes they approach more nearly to the London Clay. No sign of these deposits has been met with in the west or north of the London Basin, and they were evidently a local bank of shingle on the floor of the Eocene sea.

The **London Clay** occupies by far the greater part of the basin. It is usually a fine bluish-grey clay, which weathers brown towards the surface. It commonly contains iron-pyrites and crystals of selenite, and also layers of septaria. The last are concretionary masses consisting of a mixture of clay and carbonate of lime. In some districts they are the only hard stones available, and accordingly have been used in many of the older buildings; and they have also been employed in the manufacture of cement.

The London Clay is 400 or 500 feet thick near London, but towards the west it thins and is partly replaced by sands.

Fossils are not generally common. Amongst the characteristic forms are *Ditrupa plana*, *Aporrhais Sowerbyi*, *Aturia ziczac*, *Voluta Wetherelli*. In the Isle of Sheppey remains of plants are very abundant, and birds, turtles and snakes have also been found. The plants include leaves, stems and fruits of palms, figs, magnolias, &c., and indicate a climate much warmer than that of the present day.

The London Clay becomes sandy towards the top and passes up without a break into the Bagshot beds above. As fossils are rare and the lithological change is gradual, no very definite line can be drawn between the two formations; and it is by no means improbable that the sands of one locality may be in part contemporaneous with the clay of another.

The **Bagshot Beds** are divided into three divisions—the Lower, Middle and Upper Bagshot. The Lower Bagshot beds consist chiefly of light-coloured sand with pebble-beds in some localities and subordinate beds of clay; and generally they are strongly current-bedded. Fossils are rare, but remains of plants are occasionally found, and casts of marine shells have been met with at the top of the formation near Woking.

The Middle Bagshot is essentially a clay, but usually includes a good deal of argillaceous greensand. Fossils are not common, and are generally too imperfect for satisfactory identification; but amongst the species which have been determined are *Fusus* (*Clavella*) *longævus*, *Nummulites lævigatus* and others which are characteristic of the Bracklesham series in the Isle of Wight.

The Upper Bagshot beds consist almost entirely of light-coloured sands, usually with a thin but persistent bed of flint-pebbles at the base. The sands themselves, unlike the Lower Bagshot beds, are not false-bedded, and show very little sign of stratification. Casts of marine shells are found, including *Rimella rimosa*, *Cardita sulcata*, &c. On the whole they appear to indicate that the deposits are the equivalents of the Lower Barton beds of the Hampshire Basin.

The Hampshire Basin

The Hampshire Basin is a roughly triangular area which stretches from near Dorchester on the west to Worthing on the east, and from the middle of the Isle of Wight on the south to the neighbourhood of Salisbury on the north. It is bounded on the south by a monoclinal

FIG. 127.—SECTION OF THE ISLE OF WIGHT, TOTLAND BAY TO HEADON HILL. (After H. W. Bristow.)

a, Chalk.—EOCENE: *b*, Reading Beds; *c*, London Clay; *d*, Lower Bagshot Beds; *e*, Bracklesham Beds; *f*, Barton Clay; *g*, Barton Sand.—OLIGOCENE: *h*, Headon Beds; *k*, Osborne Beds; *l*, Bembridge and Hamstead Beds.—RECENT: *m*, Gravels.

flexure which runs through the Isles of Wight and Purbeck (cp. Fig. 127). In the steep northern limb of this flexure the strata stand nearly vertical, and the outcrops of the Chalk and Eocene are consequently very narrow. The continuity of the basin is broken by several other parallel folds, one of the most important of which runs past Chichester.

In this area the Lower Eocene, including the London Clay and the Lower London Tertiaries, is somewhat thinner than in the London district; and it appears only upon the margin of the basin. The upper beds, on the other hand, are far more fully developed, and together with the succeeding Oligocene they fill the greater part of the basin.

The general succession is as follows :—

Upper Eocene	Barton beds .	Barton Sand. Barton Clay.
	Bracklesham beds.	
Lower Eocene .	Lower Bagshot beds. London Clay. Reading beds.	

The Thanet Sands are absent and the Lower London Tertiaries are represented by the **Reading Beds** alone. These are similar in character to the Reading beds of the western extremity of the London Basin. They consist of red and white mottled clays with occasional layers of brown sand. Few fossils have been found excepting remains of plants; but at Lancing the clays include a thin layer of ironstone nodules with marine shells. The plants indicate a temperate climate, and the deposits were no doubt laid down in an estuary or lagoon.

The **London Clay** is similar to that of the London Basin, but on the whole is somewhat more sandy, especially in Dorsetshire. In the Isle of Wight it appears to thin from east to west; but in the folding to which this area has been subjected it is not possible for the strata to preserve their original thicknesses throughout.

The **Lower Bagshot Beds** consist chiefly of light-coloured sands with beds of clay. Fossils are generally rare, but in a seam of pipe-clay at Alum Bay leaves and other remains of plants have been found in abundance. Amongst the most conspicuous forms are *Ficus Bowerbanki, Aralia primigenia, Comptonia acutiloba*, &c. Like the plants of the London Clay, they indicate a warm if not a tropical climate.

Owing to the unfossiliferous nature of most of the deposits, the upper limit of the series cannot be determined with certainty. At the eastern end of the Isle of Wight a thickness of about 100 feet is sometimes assigned to the Lower Bagshot, at the western end about 660 feet. But it is probable that a considerable part of the latter may belong to the succeeding Bracklesham series.

The **Bracklesham Beds** are in part of estuarine origin and in part marine. Like the Lower Bagshot, they consist of sands and clays. But at the eastern end of the basin the argillaceous material predominates, and the difference between the two series is fairly marked. At the western end of the basin both the Bracklesham and Lower Bagshot beds consist chiefly of sands, and no very definite line can be drawn between the two formations.

The change in the character of the deposits is accompanied by a change in the fossil contents. In the east the Bracklesham beds contain an abundant fauna of Mollusca and Foraminifera; in the west remains of plants predominate, and marine fossils are limited to a small part of the series. It is evident that the eastern end of the Hampshire Basin lay beneath the sea, while the western end was occupied by an estuary.

The Bracklesham beds form the foreshore on both sides of Selsey Bill; they are well exposed in the cliffs of Whitecliff Bay and Alum Bay, at the eastern and western ends of the Isle of Wight; and they are also shown on the Hampshire coast near Bournemouth.

At Selsey Bill they have yielded a large series of marine fossils, and palm-fruits (*Nipa*) are found in the lower beds. But it is at Whitecliff Bay that the succession can be most conveniently studied. Here the deposits are yellow and green sands, sandy clays, and green and blue clays. *Nummulites variolaris* is characteristic of the upper part of the series, *Nummulites lævigatus* of the lower part. Other Foraminifera also occur, and also many marine Mollusca such as *Venericardia planicosta, Turritella imbricataria*.

At Alum Bay the lower part of the series consists of light-coloured sands, with beds of clay and seams of lignite, and contains no recognisable fossils. It is impossible, therefore, to define the lower limit of the series. But above these unfossiliferous deposits lie dark sandy clays with a marine fauna similar to that of Whitecliff Bay and Selsey Bill, but far less rich in species.

Near Bournemouth the greater part of the Bracklesham series consists of sands. The characteristic Bracklesham shells appear in some of the beds, but the principal fossils are plants, many of which are beautifully preserved. Amongst them are species of willow, palm, sequoia, araucaria, eucalyptus and ferns (*Osmunda*, &c.).

The **Barton Beds** are well exposed at Barton, on the coast of Hampshire, and also in the Isle of Wight. The lower part, which is often called the Barton Clay, consists chiefly of sandy clays, and clays with septaria. Fossils are extraordinarily abundant. *Nummulites elegans* is found near the base. The mollusca include *Crassatella sulcata, Fusus* (*Clavella*) *longævus, Xenophora agglutinans, Rimella rimosa, Voluta luctatrix*, and *Typhis pungens.*

Above the Barton Clay is a mass of yellow and white sands, known as the Barton Sands, or Upper Barton, or sometimes as the Headon Hill Sands. At the base the sands become argillaceous and contain *Chama squamosa* and other fossils. Another clayey bed occurs higher up in the series at Barton. In the Isle of Wight the sands above the *Chama* bed are generally unfossiliferous; but at Barton brackish-water shells, such as *Cerithium pleurotomoides*, occur towards the top.

Correlation Table: London and Hampshire Basins

	London Basin.	*Hampshire Basin.*
Upper Eocene	(Absent)	Barton Sand.
	Upper Bagshot beds	Barton Clay.
	Middle Bagshot beds	Bracklesham beds.
Lower Eocene	Lower Bagshot beds	Lower Bagshot beds.
	London Clay	London Clay.
	Woolwich and Reading beds	Reading beds.
	Thanet Sands	(Absent).

The Volcanic Region of Antrim and the Hebrides

During the Eocene period the north-western part of the British Isles was land, and it was the seat of an extraordinary series of eruptions. The products of these eruptions are still visible in the great basaltic plateau of Antrim; in Mull, Skye and other islands of the Inner Hebrides; and also at several localities upon the western coast of Scotland. But they are only fragments of what was once a far more extensive volcanic region. The petrographical province to which they belong includes the Faröer, Iceland, the eastern part of Greenland, and even extends to Spitsbergen and Jan Mayen. It is not possible to prove that these islands were connected, but the abrupt termination of the great series of basaltic flows at their sea-cliffs shows that the lavas formerly extended far beyond their present limits.

It is in the Isle of Skye that these rocks have been most carefully examined, and three phases of igneous activity have there been recognised:—

3. Phase of minor intrusions.
2. Plutonic phase.
1. Volcanic phase.

The first or volcanic phase was characterised by the outpouring of a vast series of basic and sub-basic lavas. Only one small patch of acid lavas has been detected. Here and there, at the base, are ashes and tuffs, indicating explosive action; but by far the greater part of the series consists of lavas which appear to have welled up quietly from fissures, without the formation of volcanic cones. The aggregate thickness of the flows exceeds 1,000 feet, apart from the sills which were intruded at a later date. The rocks are for the most part olivine-basalts, generally uniform in texture, but sometimes porphyritic. Sometimes they are highly vesicular, with numerous amygdaloids.

The volcanic phase was succeeded in Skye by the intrusion of a series of plutonic masses. The earliest of these were ultra-basic in character, generally rich in olivine, and often containing anorthite. The next stage was the intrusion of large bodies of gabbro, which now constitute the Cuillin and other hills. They are mostly olivine-gabbros, and form laccoliths rather than bosses. The later intrusions were mostly granites and granophyres. These are well displayed in the Red Hills.

Then followed the phase of minor intrusions. They were partly in the form of dykes of various composition. It is highly probable that many dykes which occur outside the region belong to this period. The Cleveland dyke, which traverses the Jurassic rocks of Yorkshire, may be cited as an example.

But of more importance than the dykes are the numerous sills which were intruded between the basalt lavas, and very greatly increased the thickness of the whole. These sills are very like the lava-flows in their general character, but usually exhibit marked columnar structure.

The age of the lavas is determined by the sedimentary deposits which are occasionally found at the base of the series or intercalated between the flows. These consist of gravel, sand, clay and lignite, and in some places have yielded remains of plants. The principal localities are Ardtun in Mull, the Isle of Canna, and Ballypalady and Glenarm in Antrim. These deposits are either soils or were formed in lakes or rivers. The plants which they contain appear to indicate an early date in the Eocene period.

B.—THE OLIGOCENE

The Oligocene system plays a very subordinate part in British geology; and if our area were alone concerned, there would be little justification for separating it from the Eocene. Formerly, indeed, the two systems were united. In Germany, however, the Oligocene is a far more important formation. At the close of the Eocene period there were very considerable changes in the geography of Western Europe. South-eastern England, which was then sea, became land, and Northern Germany, which was then land, became sea. It is chiefly on account of these changes that it has been found convenient to divide the Oligocene from the Eocene. In England the Oligocene is found only in the Hampshire Basin and in Devonshire.

Hampshire Basin.—The Oligocene covers the northern part of the Isle of Wight and a considerable area on the other side of the Solent. It rests quite conformably upon the Eocene, but was formed under different conditions. The Eocene as a whole is a marine formation with occasional estuarine intercalations. The Oligocene, on the other hand, consists of fresh and brackish water deposits, with only one or two marine beds. There is, however, no sharp line between the two systems, and the Barton Sands may belong to either.

So far as the lithological nature of the deposits is concerned, there is but one important difference between the two formations. Sands and clays form the greater part of both, but in the Oligocene there are several beds of limestone. They are not limestones of the usual type, for they are full of fresh-water shells. Similar calcareous deposits have been formed in recent times in some of the meres of the Fen District.

The marine and brackish-water fossils which occur in the Oligocene do not differ in any marked respect from those of the Eocene. The fauna is naturally not so rich, but it is of the same type. Gastropods and lamellibranchs still predominate, and the genera are all survivors from the Eocene sea.

The fresh-water fauna also consists chiefly of Mollusca, especially gastropods. Most of the genera which are found in our present ponds and rivers are represented. The common forms are the gastropods *Limnæa*, *Planorbis* and *Viviparus*, and the lamellibranchs *Unio* and *Cyrena*.

Land snails, such as *Helix* and *Amphidromus*, also occur.

Mammalian remains have been found in considerable abundance. *Hyopotamus*, *Anoplotherium*, *Palæotherium* and *Chæropotamus* are the commonest forms.

Remains of plants occur in some of the beds. The nucules of *Chara*, a fresh-water alga, although small, are conspicuous in the Bembridge Limestone.

The Oligocene of the Hampshire Basin is divided as follows :—

Hamstead Beds. Chiefly fresh-water; brackish water and marine towards the top.
Bembridge Marls. Fresh-water; marine bed near base.
Bembridge Limestone. Fresh-water.
Osborne Beds. Fresh and brackish water.
Headon Beds. Fresh-water, brackish water and marine.

But with the exception of the Bembridge Limestone, none of these divisions are very clearly defined, either lithologically or palæontologically. The whole succession appears to represent only a part of the continental Oligocene, and the true Upper Oligocene is unknown in England except at Bovey Tracey.

The Headon series consists of clays, marls, and sands, with occasional beds of limestone and seams of lignite. It is commonly divided into Lower, Middle and Upper Headon. The Lower and Upper Headon beds are of fresh-water and brackish-water origin; but the Middle Headon is to a large extent marine. *Cytherea incrassata* is the characteristic fossil of the marine beds. *Ostrea velata* sometimes forms thick banks, and many other marine shells occur. The principal fresh-water forms are *Planorbis euomphalus*, *Limnæa longiscata*, and amongst the lamellibranchs *Erodona* and *Cyrena*.

The Osborne beds near the axial line of the Isle of Wight are red and green clays with some fresh-water limestones. But in the north of the island they consist of hard grits and limestones with sands and marls above. One of the beds of clay is crowded with the remains of a small fish, *Clupea vectensis*. The principal fossils are fresh-water shells such as *Limnæa longiscata* and *Planorbis obtusus*, and brackish-water forms such as *Melania excavata*.

The Bembridge Limestone consists of hard beds of white or cream-coloured stone, separated by layers of clay or softer limestone. It is entirely a fresh-water deposit. *Planorbis discus, Viviparus orbicularis* are common; various species of the land-shells *Amphidromus* and *Helix* occur; and the nucules of *Chara* are abundant. Mammalian remains are also found.

The Bembridge marls are mostly of fresh-water origin, but at Whitecliff Bay a marine bed with *Cytherea incrassata* and *Ostrea vectensis* occurs near the base.

The Hamstead beds are also marls. The lower and larger part consists of red, green and dark-coloured clays, with *Unio, Viviparus,* and remains of reptiles, mammals and plants. These are entirely of fresh-water or estuarine origin. The upper part, about thirty feet in thickness, is also composed mostly of clay; but it contains marine and brackish-water shells, such as *Corbula vectensis, Ostrea calligera, Potamides plicatus,* &c.

Devonshire.—Between Newton Abbot and Bovey Tracey, on the Teign, is a broad low-lying tract of heath which is almost completely shut in by higher ground. This basin-shaped depression, which measures about nine miles by four, is occupied by gravels, sands and clays, which rest directly and unconformably upon the Devonian and Carboniferous rocks. Lignite occurs at the Bovey end of the basin in sufficient quantity to be worked for fuel. Plant-remains are abundant in some places, and amongst them are *Osmunda, Sequoia,* &c. These beds were formerly referred to the Bracklesham series, but have now been shown to be of Upper Oligocene age. According to Mr. Clement Reid the flora is similar to that of the lignites of the Rhine valley.

CHAPTER XXVIII

THE MIOCENE AND PLIOCENE SERIES

A.—THE MIOCENE

No Miocene deposits are known in the British Isles, and during the Miocene period not only our own country but also the greater part of Northern Europe was land. The North Sea, however, was already in existence, for marine beds of this age are present in Schleswig-Holstein, the north-west of Germany and the Netherland area. The Atlantic spread into the basins of the Loire and the Garonne. From the Mediterranean an arm proceeded around the outer border of the Alps and the Carpathians into the south of Russia, and through the Vienna gap into the plain of Hungary.

In the south of Europe it was a period of gigantic changes. A great part of the Alpine folding took place in Miocene times. Arms of the sea were cut off and for a time became salt lakes. It was in one of these that the famous salt deposits of Wieliczka were formed. Towards the end of the period the salt lakes were gradually converted into fresh-water lagoons.

Of the great earth-movements that produced these changes some indications may be seen in the south of England. The sharp monoclinal fold of the Isle of Wight belongs to this period, for it affects the Oligocene beds; and no doubt the other similar and parallel folds, and the anticline of the Weald, were formed about the same time. At least they are post-Eocene in date. These folds were accompanied by a considerable amount of over-thrusting, which is well displayed in the cliffs of the Dorset coast.

B.—THE PLIOCENE

The Pliocene (Fig. 128) differs from the preceding systems chiefly in its fauna. The greater number of the invertebrates belong to living species; but of the vertebrates the species are mostly extinct, though many of the genera still survive. Where deposition has been continuous no sharp line can be drawn between the Miocene and Pliocene; but in England, owing to the absence of the Miocene, the

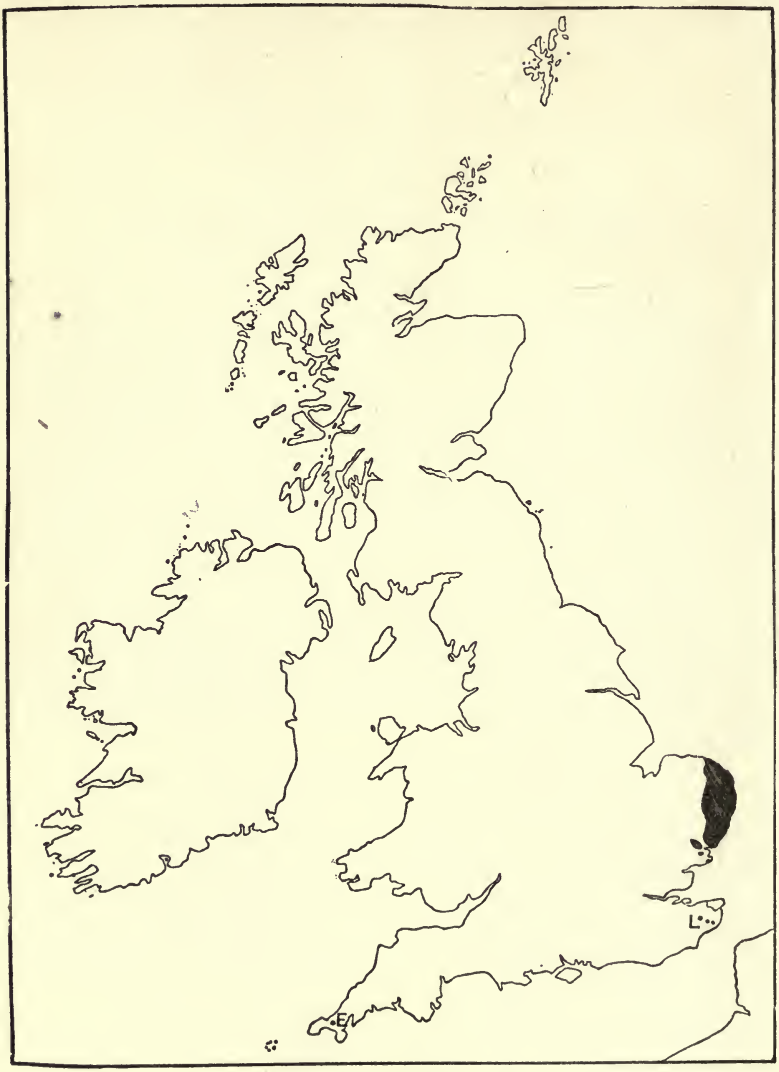


FIG. 128.—THE PLIOCENE SERIES.

L, The Lenham Beds; *E*, The St. Erth Beds.

base of the Pliocene is perfectly defined and is marked by an unconformity. The upper limit, however, is indeterminate and artificial.

In England the Pliocene consists largely of shelly sands and gravels, known locally as Crag. Often the fragments of shell form the bulk of the material. False-bedding is common, and the deposits were evidently laid down in shallow seas where tides and currents had full play. There are, however, beds of laminated clay which appear to be of estuarine origin.

The largest area of Pliocene in England lies along the East Anglian coast, extending with but little interruption from the mouth of the Stour to Weybourn, west of Cromer. Between the Stour and Walton-on-the-Naze there are a few small outliers.

Pliocene deposits also occur in patches on the Downs of East Kent, at a height of about 600 feet above the sea, thus proving that there has been a considerable amount of earth-movement since the period commenced.

Both these districts lie near the North Sea. On the other side of England a small patch of Pliocene has been found at St. Erth, south of the Bay of St. Ives, in Cornwall. In Ireland some shelly sands and gravels beneath the boulder-clay of Wexford have been referred to the Pliocene period.

Fauna.—The fauna of the English Pliocene is very rich both in species and in individuals.

Lamellibranchs and gastropods form by far the largest part. All the genera persist to the present day, and they are all inhabitants of shallow seas. Many of the species, however, are extinct; and of those which still survive, some are now found only in warmer seas, some in the northern oceans, while others continue to dwell upon our own shores. The southern forms predominate in the lower part of the Pliocene, the northern forms in the upper part.

Next to the Mollusca, the Foraminifera and Polyzoa are the most important groups. Some of the latter were formerly known as corallines, and hence the name of Coralline Crag applied to a part of the system. *Theonoa* (*Fascicularia*) and *Alveolaria* are common forms. Corals are not unknown, but they are relatively rare.

Echinoids are sometimes abundant. Amongst the genera found are *Echinocyamus* and *Temnechinus*.

Vertebrate remains are common in the nodule bed which lies at the base of the East Anglian Crags. But they are mostly derivative, and have been washed out from some older deposit. Sharks' teeth and bones of cetaceans are especially abundant; and remains of *Mastodon*, *Rhinoceros*, *Elephas* and other land mammalia are common. Terrestrial mammalia are also abundant in the Cromer Forest bed at the top of the Pliocene, and remains of birds, reptiles and amphibians have been found.

Classification.—Many minor subdivisions have been recognised in the Pliocene deposits; but it is comparatively seldom that they are found in superposition. The determination of their relative age is therefore often based upon purely palæontological evidence. In general, the older the deposit the smaller is the proportion of living forms that it contains. But it is obvious that this criterion cannot be applied except in the case of deposits which were formed under similar conditions. Evolution does not everywhere proceed with the same rapidity. In the deep seas, for example, it seems to be a slower process than in shallow water. Moreover, the rate of change is not the same throughout the animal kingdom. Thus, it has already been remarked that most of the Pliocene vertebrates are now extinct, while a large proportion of the invertebrates survive. Any comparison must therefore be restricted to a particular group or class of animals or plants. It is usual to take the percentage of living and extinct Mollusca as a standard.

Eastern England

In the east of England the following subdivisions are usually recognised:—

7. Cromer Forest-bed Series.
6. Weybourn Crag.
5. Chillesford beds.
4. Norwich Crag.
3. Red Crag.
2. Coralline Crag.
1. Lenham beds.

The **Lenham Beds** form a number of small patches on the top of the North Downs, between Maidstone and Folkestone, at a height varying from about 500 to 620 feet above the sea. In several cases they owe their preservation to the fact that they have fallen into pipes formed by the solution of the chalk beneath. They are mostly glauconitic sands. Owing to the oxidation of the glauconite the sands often become brown, or are even compacted into a kind of hard ironstone.

The Lenham beds appear to be the oldest of our Pliocene deposits. The fauna consists chiefly of shells, and is not unlike that of the Coralline Crag. It includes, however, a few species which are unknown in that formation, but have been found in the Miocene. Amongst these are *Pleurotoma Jouanneti*, *Terebra acuminata* and *Arca diluvii*.

The **Coralline Crag** is known only in the south-east of Suffolk. The principal outcrop is in the neighbourhood of Aldeburgh and Orford, but small patches occur farther south at Sutton, Ramsholt and Tattingstone (cp. Fig. 129). At its base at Sutton there is a

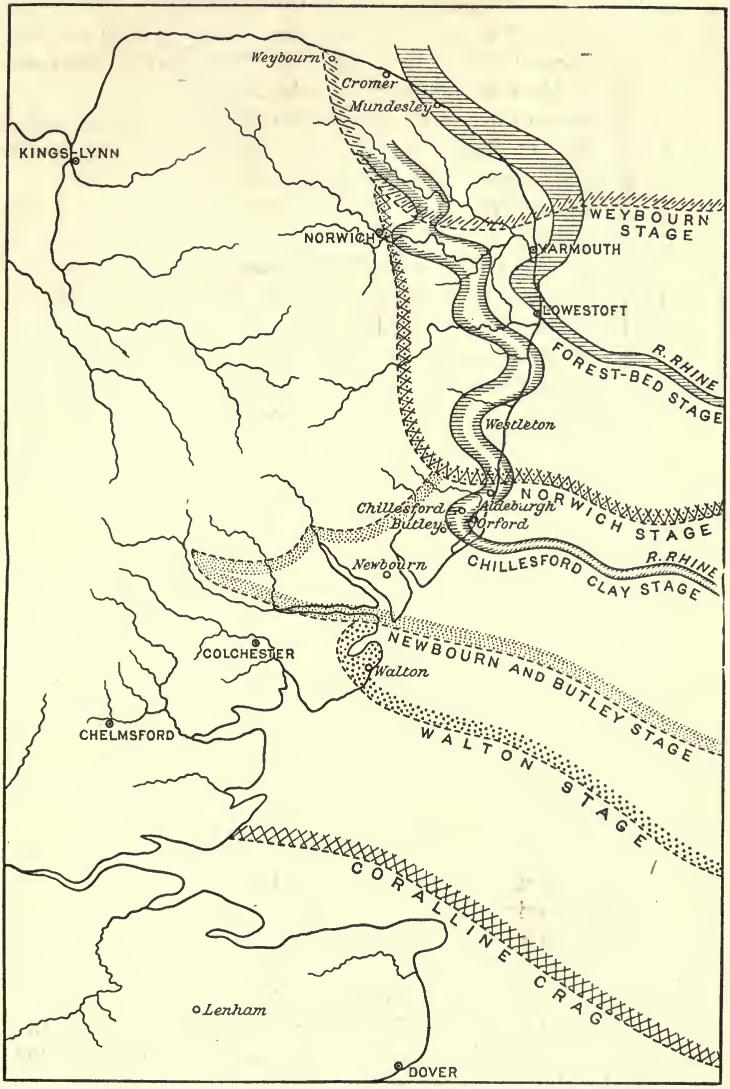


Fig. 129.—Attempted Restoration of the Distribution of Land and Water during Successive Stages of the Pliocene Epoch. (By Mr. F. W. Harmer.)

phosphatic nodule bed containing fossils derived from the London Clay below, but including also vertebrate remains, some of which may belong to the Pliocene period. There are also blocks of sandstone known as box-stones, which seem to have been derived from some deposit of about the same age as the Lenham beds.

The rest of the Coralline Crag is made of light-coloured sands and beds of comminuted shells and Polyzoa. The upper part is sometimes cemented into a soft limestone, and is darker in colour.

Amongst the common fossils are the large brachiopod *Terebratula grandis* and several species of echinoids. But far more important are the Mollusca and Polyzoa, both of which occur in such profusion as to form a large proportion of the deposit. *Theonoa aurantium* and *Alveolaria semiovata* are two of the common polyzoans. Of the Mollusca some 30 or 40 per cent. are extinct. *Astarte Omalii* and *Voluta Lamberti* may be cited as examples. Of the species which still survive, about 20 per cent. no longer live so far north, but are found in the Mediterranean, as, for example, *Cardita corbis*, *Limopsis pygmæa* and *Ringicula buccinea*. It is evident, therefore, that during the deposition of the Coralline Crag the British seas were warmer than they are at present.

At the present day the **Red Crag** is practically confined to a triangular area about the mouths of the Stour and Orwell, with Walton-on-the-Naze, Sudbury and Aldborough at the three corners. But it may have had a greater extension, and doubtful traces have been found as far away as Thaxted in the north-west of Essex. It is usually a red or brown shelly sand deeply stained by oxide of iron. Generally it is darker than the Coralline Crag, but the colour of both is variable. On the whole, too, it is more quartzose and less calcareous, but nevertheless some of the beds are made up largely of fragments of shells. There is often a nodule bed at its base.

Before the Red Crag was deposited the Coralline Crag had been almost entirely worn away. Here and there, however, it was left as reefs or shallows in the Red Crag sea. Accordingly the Red Crag generally rests upon an eroded surface either of the London Clay or of the Coralline Crag, and at Sutton it is banked against the latter as a beach is banked against a cliff (cp. Fig. 130).

The fauna of the Red Crag is rather more modern than that of the Coralline Crag. But there are considerable variations in the Red Crag itself. At the Naze it contains a smaller percentage of living species than at Newbourn, and at Newbourn a smaller percentage than at Butley. That is to say, the proportion of living forms increases from south to north. The sea-coast lay towards the south, and gradually the deposits spread northwards from the shore ; and thus the southern part of the Red Crag is older than the northern.

Not only is the fauna newer than the fauna of the Coralline Crag, but it is also of a more northern type. The Coralline Crag contains a number of species which no longer live in the German Ocean, but are found in the Mediterranean Sea. The Red Crag also includes forms which do not now inhabit the neighbouring waters. Some of them still dwell in more southern seas, but others are now found only in the boreal ocean. From Walton to Butley the proportion of southern forms diminishes and the proportion of northern forms increases. This is clearly shown in the table on p. 471.

The fauna of the Red Crag is very rich both in species and individuals. Polyzoa, however, are rare except in the Walton deposit, which in other respects also shows affinities to the Coralline Crag. Gastropods and lamellibranchs predominate. *Venus casina*, *Pectunculus glycimeris* and *Neptunia contraria* are common forms of which the first two still live in British waters and occur also in the Coralline Crag. *Admete viridula*, *Cardium* (*Serripes*) *grœnlandicum* and *Nuculana lanceolata* are species which are now known only in more northern seas. The small echinoid *Echinocyamus pusillus* occurs in profusion at Walton and elsewhere.

The **Norwich Crag** begins at Aldeburgh where the Red Crag ends, and extends along the Suffolk and Norfolk coasts as far as the river Bure. It thickens rapidly from south to north, and also from west to east, and is about 150 feet in thickness at Southwold. It consists of sands and clays and pebbly gravels, but never exhibits the beach-like bedding characteristic of the Red and Coralline Crags. Moreover, it is less

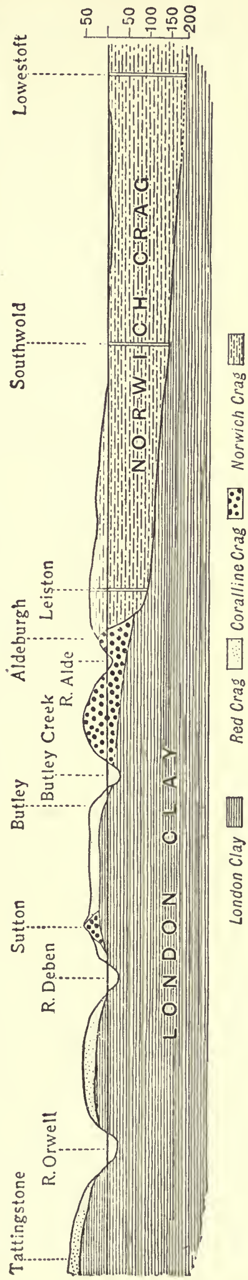


Fig. 130.—Section from Tattingstone to Lowestoft. Showing the relations of the Coralline Crag, Red Crag, and Norwich Crag, and the rapid thickening of the Norwich Crag northwards. (After Mr. F. W. Harmer.)

uniformly fossiliferous. In many of the sections no organic remains have been found; but in others impersistent shelly beds occur, which have yielded an abundant fauna. On the whole, it appears to

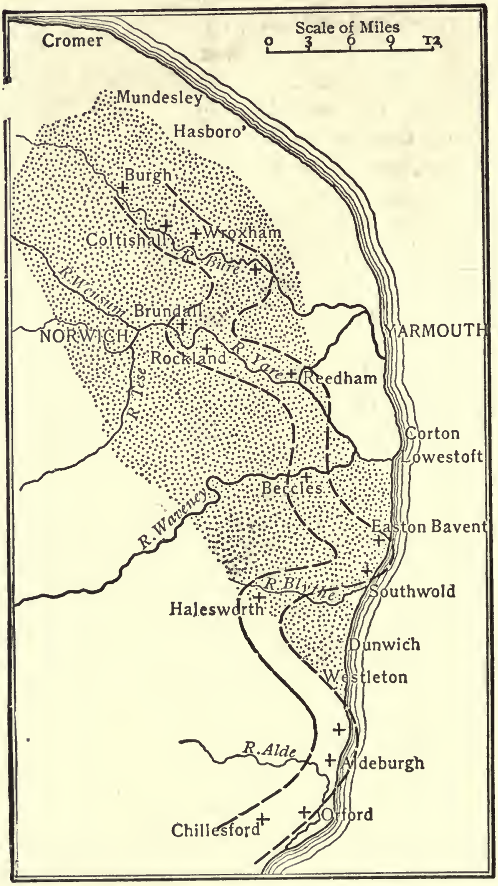


FIG. 131.—MAP SHOWING THE PRINCIPAL EXPOSURES OF THE CHILLESFORD CLAY (+) AND THE PROBABLE COURSE OF ONE OF THE ESTUARIES OF THE RHINE DURING THE CHILLESFORD AGE. (After Mr. F. W. Harmer.)

be a delta deposit rather than a beach or sand-bank. At the base is a bed of flints and pebbles in which mammalian remains have been found, as in the nodule bed at the bottom of the Red and Coralline Crags.

A considerable interval of time appears to have elapsed between the deposition of the Norwich and the Red Crags, for the two faunas are decidedly distinct. In the Norwich Crag the proportion of extinct forms is less, and the proportion of northern forms considerably greater. The change that began in the Red Crag period was continued and the climate was growing colder.

The fauna of the Norwich Crag is less rich than that of the preceding stage. Of the common species of Mollusca nearly two-thirds live in the North Sea at the present day. Others, such as *Nucula Cobboldiæ* and *Tellina obliqua*, are extinct; and others are now found only in Arctic waters. *Astarte borealis* is the most important of the Arctic forms. It is abundant at Norwich, but becomes less common towards the south, and is unknown in the southern part of Suffolk.

The deposit which appears to be the next in order is the **Chillesford Clay** (Fig. 131). In the Bure Valley it rests upon the Norwich Crag; in the south of Suffolk it lies upon the Red or the Coralline Crag. It is in general finely laminated, consisting of alternations of clay and sand, both of which are very micaceous. The fauna is marine.

The Chillesford Clay extends from Chillesford to Burgh in the valley of the Bure; but from west to east its extent is very limited. The exposures which are referred to it are confined within a narrow and meandering belt of country which widens from south to north. It has been suggested by Mr. F. W. Harmer that this belt represents an estuary of the Rhine, and that the open sea had retreated to the north.

In the north of Norfolk is another shelly deposit known as the **Weybourn Crag.** It is found on the coast west of Cromer, and has been recognised in the valley of the Bure, but south of Norwich it is unknown. Its thickness is small, and its special feature is the great abundance of *Tellina balthica*, a shell which is quite unknown in the older beds.

The following table, drawn up by Mr. F. W. Harmer, shows the gradual increase of living and of northern forms from the period of the Coralline Crag to that of the Weybourn Crag. It refers only to the Mollusca, and takes account only of species which are characteristic and abundant.

	Not known Living.	Living only in distant seas.	Southern.	Northern.	Northern and Southern.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Weybourn Crag	11	..	..	33	56
Norwich Crag	11	..	7	32	50
Red Crag — Butley	13	4	13	23	47
Red Crag — Newbourn	32	5	16	11	36
Red Crag — Walton	36	4	20	5	35
Coralline Crag	38	4	26	1	31

Following the Weybourn Crag is the remarkable series of deposits so well displayed in the Cromer Cliffs, and known as the **Cromer Forest-bed Series.** This is made up of several beds, as follows :—

5. Arctic plant-bed.
4. *Yoldia* (*Leda*) *myalis* bed. Marine.
3. Upper fresh-water bed.
2. Forest bed.
1. Lower fresh-water bed.

The *Yoldia* (*Leda*) *myalis* bed and the Arctic plant-bed are often included in the Pleistocene, and the name of Cromer Forest-bed series limited to the other three. But it is very doubtful whether this division agrees with the limits adopted elsewhere, and it will be convenient to describe the whole succession together.

The principal interest of these deposits lies in the Forest bed and the Arctic plant-bed. The former consists of irregular layers of clay, sand and gravel, with stumps and stems of trees. The roots of the stumps are frayed and worn, and it is apparent that the trees are not where they originally grew, but have been washed into their present positions. Both the trees and the other remains of plants associated with them belong for the most part to species that live in East Anglia at the present day. The Forest bed also contains mammalian remains, such as *Elephas*, and a mixture of marine and fresh-water shells, including *Tellina balthica*. The fresh-water beds above and below contain plant-remains, land and fresh-water molluscs and small vertebrates. The lower fresh-water bed is seldom preserved.

The *Yoldia myalis* bed is a false-bedded loamy sand about 10 or 15 feet thick. The fossils are marine, but are not often abundant. *Yoldia myalis*, *Astarte borealis* and *Tellina balthica* are all present.

The Arctic plant-bed or Arctic fresh-water bed is a thin and discontinuous layer of clay or loam which contains the wing-cases of beetles, various land molluscs and also plant remains. The latter include the dwarf willow (*Salix polaris*) and the dwarf birch (*Betula nana*), and other forms which now live within the Arctic circle.

West of England

The only deposits in the west of England which can with certainty be referred to the Pliocene period are those of St. Erth, in Cornwall. They lie at a height of about 100 feet above the sea, in the depression which runs from St. Ives Bay to Mounts Bay. The area occupied is not more than a few acres in extent.

The St. Erth beds are composed of loam, sand, and clay, with a little coarser material. The clay is only a few feet thick, but it has yielded about 90 species or marked varieties of Mollusca and 120 Foraminifera. Southern species of Mollusca occur, but no northern forms. Most of the Mollusca are found also in the older part of the Red Crag, and it is with this horizon, or with the Coralline Crag, that the St. Erth beds are provisionally correlated.

Ireland

Beneath the boulder-clay of Wexford, deposits of sand and gravel have been found which have yielded a rich molluscan fauna. Some of the beds, as in the East Anglian Crags, are made up largely of comminuted shells. Most of the species still live on the Irish shores, but a few are extinct and some are Mediterranean forms. The fauna is apparently Pliocene, and is believed to be somewhat more recent than that of St. Erth.

CHAPTER XXIX

THE PLEISTOCENE SERIES

The gradual influx of northern shells during the progress of the Pliocene period shows that the East Anglian Sea was slowly growing cold; but almost to the end of that period the flora and fauna of the land gave little indication of the change. The remains in the Cromer Forest bed prove that the climate was still temperate.

At last, however, the increasing cold resulted in the advent of Arctic conditions upon the land itself, as is shown by the presence of the dwarf birch and similar plants a few feet above the Forest bed of Cromer.

Arctic conditions were not confined to the British Isles, but were universal over Northern Europe. All the mountain regions bear evidence of glacial action, in the form of roches moutonnées, striated rock-surfaces, terminal moraines, and erratic blocks. In the plains the boulder-clay with its scratched and polished boulders is clearly due to the action of ice, though it is not admitted by everyone as evidence of glaciers.

Farther south the glaciers of the Alps spread far beyond their present limits, and there are signs of glacial action even in the mountains of the south of Spain and Italy.

So much is generally admitted; and few geologists would be disposed to deny that during the early part of the Pleistocene period the climate of Northern Europe was cold, but beyond this there is no universal agreement.

In Northern Europe, therefore, the Pleistocene period may be divided into an earlier cold or Glacial epoch and a later post-Glacial epoch. According to some writers, the Glacial epoch was really a series of cold periods separated by warm intervals.

The deposits may similarly be divided into two stages—

2. The Post-glacial stage.
1. The Glacial stage (often known as 'Drift').

But as the north would naturally remain cold longer than the south, these divisions cannot have any very precise significance.

The most remarkable of all the Pleistocene deposits is the boulder-clay or till, and it is concerning this that the fiercest controversies rage. It is found in the valleys of the mountain districts, and often covers the whole surface of the lowlands. It is generally a firm and very tenacious clay, in which boulders of various sizes are imbedded. These boulders are quite distinct from the stones of other deposits. They are neither angular like the material of a scree nor rounded like the pebbles of a beach. The edges are worn and the faces smoothed as if by emery, but the polished surface is scored with grooves or scratches, usually parallel to the length of the boulder. Many of the boulders have come from great distances. Scandinavian boulders, for example, are scattered over the north of Germany, and are often found in the east of England.

A typical boulder-clay shows no sign of stratification, and there is no sorting of the coarse and fine material. But sometimes wisps of sand occur, and sometimes definite layers of sand or silt or gravel. In some districts these less characteristic boulder-clays contain marine shells.

It is generally admitted that the boulder-clay owes its origin to ice, but there are strongly divergent opinions as to the manner in which it was deposited and the condition of Europe at the time.

According to the view most widely accepted, Northern Europe during the Glacial period resembled the Greenland of the present day. A great ice-sheet covered the British Isles, Holland, North Germany, the North Sea, Denmark, Scandinavia and a large part of Russia. The ice flowed outwards from the Scandinavian highlands as a centre, and there were minor centres in Scotland, the Lake District, North Wales and elsewhere. It was this ice-sheet that brought Norwegian boulders to our shores and scattered Scottish and Cumbrian rocks over the plains of Cheshire.

But this hypothesis is not free from difficulties. Unless the Scandinavian hills were higher than they are at present, or unless they were covered by an almost incredible thickness of snow, it is not easy to understand how the ice could reach our shores. The highest point in Norway is about 8,400 feet above the sea, and the distance to the nearest point of the Scottish coast is about 400 miles. This gives an average slope of less than a quarter of a degree, which seems hardly sufficient to force the ice across even so shallow a depression as the North Sea. It has been suggested that the ice-sheet was buoyed up by the water. But the North Sea is very shallow. Most of it is less than fifty fathoms deep; and as the specific gravity of ice compared with sea-water is about 0·875, an ice-sheet only 350 feet in thickness will strand in fifty fathoms.

On account of these and other difficulties some geologists believe that during the Glacial period the greater part of Northern Europe was submerged. Only the mountain regions rose above the water. They were covered with glaciers which reached the sea and then gave birth to icebergs. It was the melting bergs that dropped the clay and boulders where they are now found, often many hundreds of miles from their original home. The total absence of stratification and of shells in so much of the boulder-clay is perhaps the chief objection to this hypothesis.

It would take up too much space to discuss these rival theories and the numerous modifications which have been suggested; but there is still another point on which there are great differences of opinion. Some geologists consider that the glacial deposits indicate a single period of continuous cold, and they look upon the sands and gravels which are often interstratified as the deposits of glacial rivers. The individual ice-sheets fluctuated owing to local variations in the meteorological conditions of the region.

Other writers point to the presence of remains of animals and plants in some of the interbedded deposits, and argue that they indicate a warm interval between two periods of cold. There would thus be two glacial epochs and one interglacial.

A third view is held by other observers. According to this, there are several horizons at which organic remains occur; and there were several glacial epochs and several interglacial.

The Glacial Deposits

In England glacial deposits with boulders of northern origin extend southwards to a line joining the Bristol Channel and the mouth of the Thames. On the Continent the line is continued with a general easterly direction through Holland and Germany to the middle of Russia, where it bends towards the north. South of this line the northern boulders cease and no glacial deposits are found excepting in the immediate neighbourhood of mountain-chains.

The character of the deposits varies so greatly from place to place that nothing like a full description can be attempted, and only a short account can be given of a few typical districts.

The East Anglian District.—In Suffolk, Norfolk and the neighbouring counties, five divisions of the glacial deposits can be recognised, namely:—

5. Plateau Gravels.
4. Chalky Boulder-clay.
3. Mid-glacial Sands
2. Contorted Drift.
1. Cromer Till.

The Cromer Till rests upon the Arctic fresh-water bed or some other division of the uppermost Pliocene. It is a tough and unstratified bluish-grey clay with glaciated fragments of chalk, flint, various Jurassic rocks, Carboniferous limestone, and igneous and metamorphic rocks of various kinds. Many of the boulders are clearly of northern origin, and amongst the igneous rocks are some which have certainly come from Norway, including the characteristic and readily recognised rhombporphyry of the Christiania region. Sometimes the Cromer Till is divided into two by a band of laminated clay. Inland, and also towards the west, it appears to become indistinguishable from the Contorted Drift.

The Contorted Drift is the most striking feature of the Cromer cliffs. It forms a more or less continuous sheet in the north and east of Norfolk, and outliers appear even as far south as Bury St. Edmunds and Sudbury in Suffolk. Towards the chalk escarpment it is overlapped by the Chalky Boulder-clay. It is a yellowish or brownish loam with seams of gravel, sand and clay, and contains stones and boulders of various sizes. Unlike a typical boulder-clay it is distinctly stratified, but the stratification is irregular and is twisted and contorted in the most extraordinary fashion. At Cromer it includes enormous blocks of chalk, some of which are 100 or 200 yards in length. Like the Cromer Till, it contains boulders of northern origin. Towards Norwich and Yarmouth the drift loses its contorted character, but still contains boulders of igneous rock, which appear to have come from the north of England.

The Mid-Glacial Sands occur in the east of Norfolk and Suffolk, where they lie between the Chalky Boulder-clay and the deposits which are correlated with the Contorted Drift. They contain marine shells and ostracods, which are generally of a northern character.

The Chalky Boulder-clay does not take part in the Cromer cliffs; but inland it rests upon the Contorted Drift. Moreover, it spreads far beyond the limits of the latter, extending southwards to Muswell Hill in the north of London, westwards as far as Warwickshire, and northwards into Lincolnshire (Fig. 132). In general it is characterised by the great abundance of grey flints and fragments of hard chalk which it contains. Frequently, too, it contains fossils and fragments derived from the Jurassic rocks, but Scandinavian and northern boulders are rare. The matrix is generally a stiff grey clay, but varies somewhat according to the nature of the strata from which it is derived. It appears to have been formed very largely from the Mesozoic clays of Central England.

Thus while the Cromer Till and Contorted Drift are to a large extent of foreign origin, the Chalky Boulder-clay is essentially a home production. The ice-flow which brought the earlier deposits must

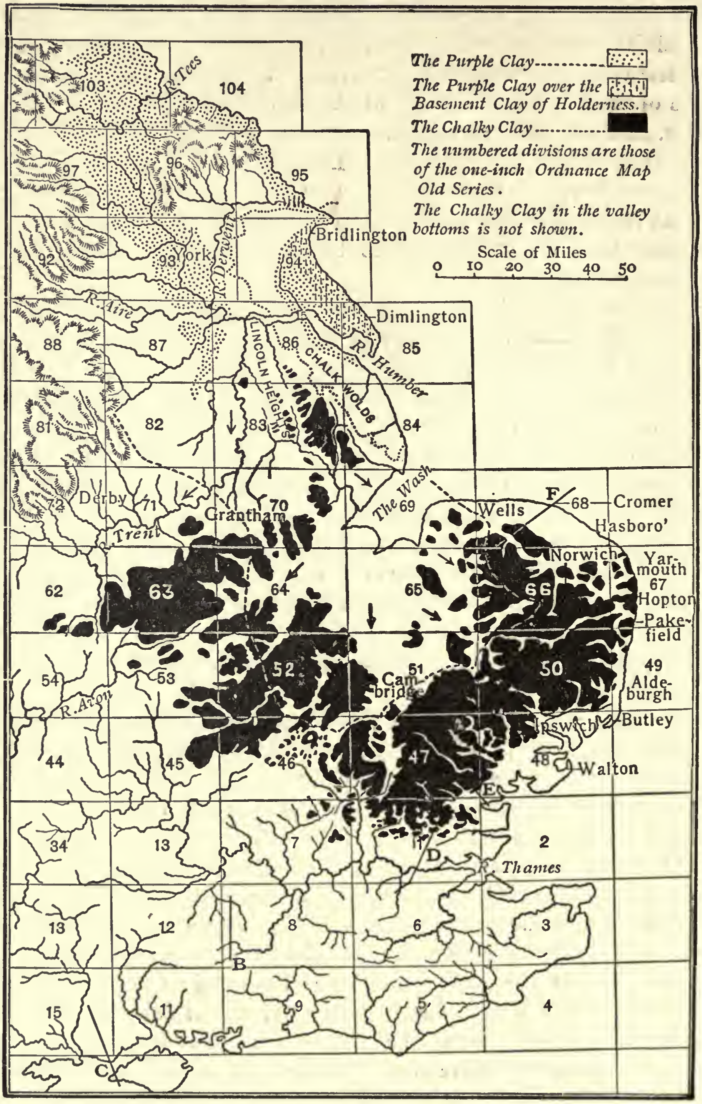


FIG. 132.—MAP SHOWING THE DISTRIBUTION OF THE PURPLE AND CHALKY BOULDER-CLAYS OF THE EAST OF ENGLAND.
(After the late S. V. Wood, jun.)

The arrows show the suggested direction of flow of the ice, and are inserted by Mr. F. W. Harmer.

have come from north and east, while the flow which brought the Chalky Boulder-clay came rather from the north and west. Owing to the hardness of the chalk fragments and the frequent presence of red chalk, it appears probable that the Lincolnshire Wolds were a centre of dispersal. The flints, too, resemble the grey flints of Lincolnshire and Yorkshire, rather than the darker flints of the southern chalk.

The Plateau Gravels cap many of the somewhat flat-topped hills of this region. Generally they lie upon the Boulder-clay. They are made up chiefly of flints, which are often rounded, but are also often broken and angular. Pebbles of hard chalk are common in places, and occasional pebbles of quartzite and other rocks are found. The origin of these gravels is by no means clear. Usually they lie upon the highest ground, but do not occur in the valleys, even where these are of pre-glacial age. Apparently the valleys must have been filled either with boulder-clay or with snow or ice when the gravels were laid down.

Lincolnshire and East Yorkshire.—The Chalky Boulder-clay is continued into Lincolnshire, but is limited on the east by the escarpment of the Chalk. On the seawards side of this escarpment the glacial deposits are entirely different in character. The clays are reddish-brown or purple in colour, and are not derived to any large extent from the Chalk. Similar deposits occur in the south-east of Yorkshire, where they have been divided as follows :—

Sewerby Gravels.
Hessle Boulder-clay.
Purple Boulder-clay.
Basement Clay.
Chalky Rubble.
Infraglacial beds.

The Infraglacial beds are seen at Sewerby and Speeton (Fig. 133). They consist of blown sand, beach sand and gravel, rainwash, &c., and are banked against an ancient cliff of chalk, which is now buried beneath the glacial deposits. Remains of *Elephas antiquus*, *Rhinoceros*, *Hippopotamus* and other mammalia have been found, and also shells of terrestrial and marine mollusca. They appear to indicate a fairly temperate climate.

The Chalky Rubble is only a few feet thick but is very constant. It is sometimes fine-grained, sometimes gravelly in character.

The Basement Clay is dark in colour and often contains large masses of Lias and irregular shelly patches with an Arctic fauna. Both the Lias and the shelly sands and clays are believed to have been transported by ice.

The 'Purple' Boulder-clay is sometimes purplish-brown or

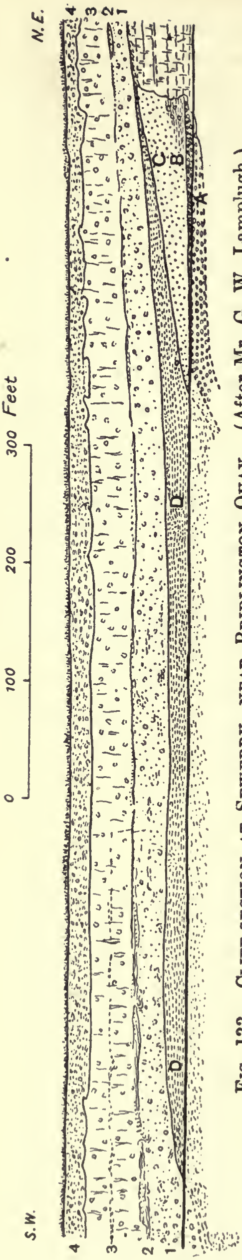


FIG. 133.—CLIFF-SECTION AT SEWERBY, NEAR BRIDLINGTON QUAY. (After Mr. G. W. Lamplugh.)

Glacial Drifts.

4. The Sewerby gravels.
3. 'Purple' Boulder-clay, splitting south-westward into two bands, with stratified material intervening.
2. Stratified clay, loam, sand and gravel, nearly thinning out north-eastward.
1. Basement Boulder-clay, with contorted patches of loam, &c.

Infraglacial Beds.

D, Chalk-rubble.
C, Blown sand, with bones, &c.
B, Land-wash banked against the ancient cliff, with bones and land shells.
A, Old sea-beach, with bones and marine shells.

purplish-blue, but the colour varies greatly according to the amount of weathering which the clay has undergone. Sometimes there are distinctly stratified layers of sand and gravel in its midst; sometimes it becomes a complex and variable series of silt, sands, gravels and bands of boulder-clay. Fragments of marine shells occur, but unbroken specimens are very rare.

The Hessle Boulder-clay is redder in colour, more earthy and less compact than the clays below, but is not always easy to distinguish.

Of the boulders that are found in these various clays, the greater number are of Palæozoic rocks, which have presumably come from Scotland and the north of England. Mesozoic rocks are also common; and occasionally, indeed, they form about half the total. There is, however, a small proportion of boulders that are undoubtedly of Scandinavian origin. Apparently the ice which deposited the clays came from the north and east.

The Sewerby gravels are not like the Plateau gravels of the East Anglian district. They do not cap the hills, but are found chiefly where the valleys of the Wolds open on to the plains of Holderness.

The Western District.—In the interior of the mountain masses of North Wales and the Lake District, the glacial deposits are entirely of local origin, and evidently these regions were covered by their own independent ice-sheets or glaciers. But on their borders, and on the low-lying plain of Lancashire and Cheshire, much of the material has been derived from distant sources.

On the north coast of Wales from Colwyn Bay eastwards the glacial deposits may be divided as follows :—

4. Boulder-clay with northern boulders and marine shells.
3. Sands and gravels ,, ,, ,, ,,
2. Boulder-clay ,, ,, ,, ,,
1. Boulder-clay with Welsh boulders and no shells.

The lowest of the boulder-clays is generally found only in the neighbourhood of the mountains, but Arenig boulders occur as far east as Birmingham.

The boulder-clay with northern boulders overspreads the plain of Lancashire, Cheshire and Shropshire. It occurs also on Anglesey and the Lleyn Peninsula, and even in Pembrokeshire; but nowhere does it penetrate far into the interior of Wales.

In Lancashire and Cheshire, as on the north coast of Wales, shelly sands and gravels are common in the midst of this boulder-clay; but they are quite irregular in distribution, and do not occur at any constant horizon. The clay itself often contains shells.

The most remarkable of the shelly deposits are those which occur on Moel Tryfan, near Snowdon, at a height of 1,350 feet above the sea; at Gloppa, near Oswestry, at a height of 900 to 1,160 feet, and at one or two other localities at similar elevations. These have been held to prove submergence in the midst of the glacial epoch; but another suggestion is that they have been brought from the bottom of the Irish Sea by the glacier which brought the northern erratics.

Distribution of Erratics.—The above descriptions will suffice to give some idea of the complexity of the English glacial deposits. In Scotland and in Ireland by far the greater part is of local origin. These countries were not invaded to any considerable extent by foreign ice.

It may be useful here to give a summary of the distribution of some of the more important rock-types which have been recognised as boulders in the English glacial deposits (Fig. 134).

Of the Scottish rocks, the riebeckite micro-granite of Ailsa Craig, in the Firth of Clyde, and the granites of Galloway are amongst the most easily recognised.

They are found in the Isle of Man, Anglesey, the Lleyn Peninsula and Pembrokeshire, and also along the north coast of Wales, and scattered over the plain of Lancashire and Cheshire. Further, they extend up the Solway Firth and crossed the Pennines into the valley of the Tyne.

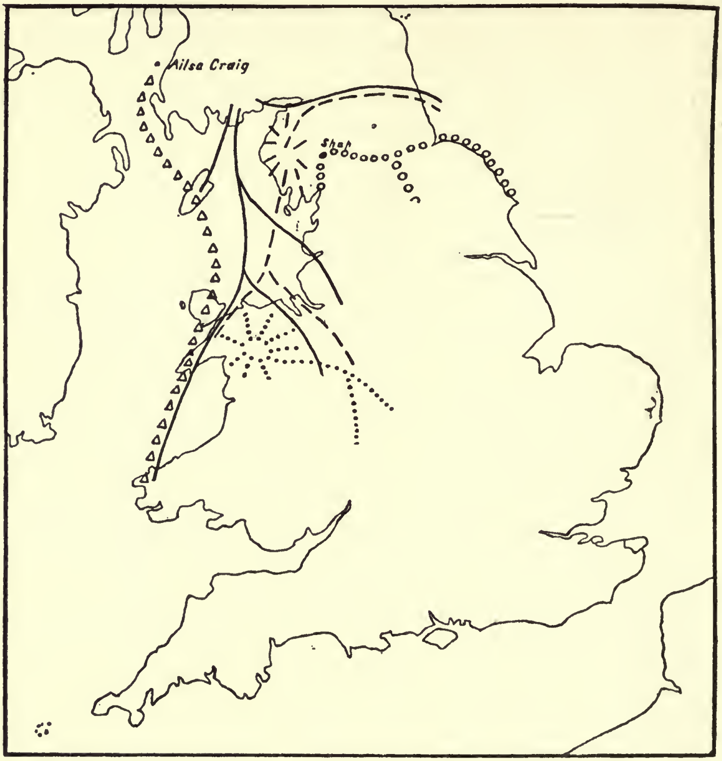


Fig. 134.—Map showing General Direction of Travel of certain characteristic Rocks.

Ailsa Craig rock shown by small triangles, Galloway granites by continuous lines, N. Welsh rocks (especially Arenig volcanics) by dots, Shap granite by small circles, other Lake District rocks by broken lines.

Amongst the Lake District rocks the Shap granite and the Ennerdale granophyre aie two of the best known. The Shap granite does not occur as boulders to any great extent upon the west side of the Pennine Chain. But other Lake District rocks are found upon the north coast of Wales and spread over Lancashire and Cheshire along with rocks of Scottish origin. The Shap granite boulders cross the Pennines by the Pass of Stainmoor and extend down the valley of the Tees. There they divide into two streams. One stream continues down the Tees and bends southwards along the Yorkshire coast. The other stream enters the valley of the Ouse and extends southwards as far as Selby.

Of the Welsh rocks, the ashes of Arenig are the type which has been most generally recognised. Boulders derived from Arenig are widely spread over North Wales. They enter the Shropshire plain at the mouth of the Vale of Llangollen, and then seem to follow a south-easterly course across Shropshire and Staffordshire, and finally cease in the neighbourhood of Bromsgrove and Birmingham.

On the ice-sheet hypothesis this distribution is explained as follows. The south of Scotland, the Lake District and North Wales each had its own ice-sheet flowing outwards from a central point. But the Scottish ice-sheet, being farther north and having a more extensive gathering ground, was the largest. It was not able to overflow the Lake District, but it deflected the local ice-sheet on the east across the passes of the Pennines and on the west into the Irish Sea. In the Irish Sea the two flowed together to the coast of Wales. The Welsh ice prevented them from overspreading the mountains; but the flow divided and overrode the lower land of Anglesey and the Lleyn Peninsula on the one hand, and entered the plain of the Mersey and Dee on the other.

The Post-Glacial Deposits

In the British Isles the most important of the post-glacial accumulations may be grouped under the following heads: cave-deposits, river-alluvia, and peat-mosses. But the formation of all three proceeded simultaneously.

The post-glacial epoch is the Age of Man. In various parts of the world evidence has been brought forward that he existed at a much earlier date, even during the Miocene period, but the evidence is open to question. There can, however, be little doubt that man existed in some parts of the world before the Ice Age of Northern Europe, and the evidence which has now been accumulated seems to prove that he lived in England during the warmer phases of the Glacial Period, if not actually in pre-glacial times. But up to the present it is only in a few localities that such evidence has been found.

It is seldom that a human skeleton or even an isolated human bone is found except in the more recent deposits. The remains of man that usually occur are the implements and weapons that he fashioned. The earliest were of stone, then followed bronze, and lastly iron. The study of these implements is not the province of stratigraphy. By the time that bronze came into use the British Isles had already assumed their present form. No geological changes of any importance have since occurred, hardly even any changes in fauna, excepting those which man himself has brought about. Here, then, geology ends and archæology and history begin.

But there still remains the Stone Age to be considered, when man was unacquainted with the use of metals. The stone implements which are found in Britain are obviously of two distinct types. Some are rudely formed and are only roughly chipped into shape; others are much more highly finished and are sometimes beautifully polished. The former are known as Palæolithic, the latter as Neolithic. In general the Palæolithic implements are older than the Neolithic, but they represent different stages of civilisation rather than different periods; and it is highly probable that Palæolithic man in England may have been contemporary with Neolithic man in more favoured regions. Moreover, it must not be assumed that Neolithic man invariably gave the highest finish to every weapon that he began.

Nevertheless, in the British Isles the Palæolithic and Neolithic periods are sufficiently distinct.

Palæolithic.—Palæolithic remains are unknown in Scotland and the north of England. But they occur in some of the caves of the Southern Pennines and of the south-west of England. They are found also in some of the older gravels and brick-earths of the south of England, generally on terraces at a considerable height above the present rivers.

Associated with the implements of human manufacture are the remains of large mammalia which are now extinct. Amongst these are the mammoth (*Elephas primigenius*), the woolly rhinoceros (*Rhinoceros tichorhinus*), the cave-hyena (*Hyæna spelæa*), cave-bear (*Ursus spelæus*), the Irish elk (*Cervus giganteus*) and other forms. There was also a hippopotamus which appears to be indistinguishable from that of the present day. The remains of *Bos primigenius*, which seems to be identical with the urus of Julius Cæsar, are abundant; and the reindeer and other living species are also found. Many of these were certainly adapted for a cold climate; but others, such as the hippopotamus, suggest a relatively high temperature. It should, however, be remembered that the mammoth and rhinoceros, which are now known to have possessed a woolly coat, would at one time have been supposed to indicate a tropical climate.

During the Palæolithic period it is believed that the British Isles were connected with the Continent. It is not easy otherwise to understand how the Neolithic fauna was introduced.

Neolithic.—Remains of Neolithic age are found in many caves, and in artificial excavations in the chalk which appear to have served as dwellings. They occur also in alluvial deposits which lie at no great height above the present rivers, in peat-mosses such as those of Ireland and the Fenland, and not unfrequently in superficial soil. Many barrows or tumuli have proved to be the tombs of Neolithic man. Often they contain several human skeletons, as well as stone weapons, fragments of pottery and other manufactured articles.

The fauna was now decidedly different from that of the Palæolithic period. Most of the large mammalia had become extinct. But still there remained the elk, the reindeer, the bear, the urus and other forms which no longer live in England. With a few exceptions, however, the fauna was similar to that of Northern and Central Europe at the dawn of history.

Presumably, therefore, the climate was nearly the same as it is at present. Moreover, the general configuration of the land has altered little. The rivers have cut a few feet deeper; in some places the sea has encroached upon the land, in others the land has gained upon the sea. But the changes are insignificant, and geologically the Neolithic age may be looked upon as the beginning of the present period.

CHAPTER XXX

THE GEOLOGICAL HISTORY OF THE BRITISH ISLES

In the preceding pages an attempt has been made to determine the condition of the British area during the successive periods described. But it will probably be convenient to the student to summarise the changes that took place—to give, in fact, a connected history of the region. In such a general account all minor details must be omitted, and in order to reduce it to its simplest form the manifestations of volcanic activity are here omitted and are dealt with separately in the next chapter.

The First Continental Period.—So far as is known, the oldest rocks in the British Isles are the Lewisian gneisses and schists of the north-west of Scotland. They are for the most part of deep-seated origin, and afford no clue as to the conditions that prevailed on the surface when they were formed. It is, however, certain that they were greatly sheared and folded before the Torridon Sandstone was laid down. There was, therefore, between Lewisian and Torridonian times, a period of great earth-movement, the earliest of which we have any evidence in our area.

Before the Torridonian beds were deposited, the rocks that covered the Lewisian gneiss were removed and the gneiss itself was exposed to the action of the atmosphere; for the surface on which the Torridon Sandstone rests is rugged and irregular, and had evidently been carved into hills and valleys by rivers and other subaerial agencies. The sandstone itself is a subaerial deposit; and therefore it is clear that during the Torridonian period, and for some time previously, the north-west of Scotland was land. Similar evidence in Norway shows that the land extended into Scandinavia, and probably a continent occupied the north-western part of Europe.

The limits of the continent are not known. It is uncertain whether the pre-Cambrian volcanic rocks of Wales and the Midlands were laid down upon its surface or in a sea that washed its southern shores.

The First Marine Period.—In Cambrian times the continent was invaded by the sea, which spread northwards at least as far as the north of Scotland. The subsidence that rendered the invasion possible was not accompanied by folding, for the Torridonian beds show little sign of disturbance. But as the land sank its surface was denuded, and consequently the Cambrian strata rest unconformably upon the older rocks.

During the Ordovician and Silurian periods the greater part of our area still lay beneath the sea, and deposition proceeded almost continuously. There were, indeed, occasional and local interruptions. In North Wales the Arenig beds lie unconformably upon the Cambrian, and the Llandovery is usually unconformable to the Ordovician. But the unconformities are slight, and do not indicate earth-movements of any considerable magnitude.

The Second Continental Period.—The sandy nature of the Downtonian beds shows that at the close of the Silurian period the sea was gradually becoming shallow. The north-western continent was again emerging, and was spreading southwards. At the same time, the deposits that had been laid upon its southern margin were crushed and folded against it. Generally the folds trend from south-west to north-east, and they affect the Silurian and older rocks of the north of Ireland, the north of Wales, the Lake District, the Southern Uplands and the Highlands of Scotland, and also the rocks of Norway. The cleavage and foliation of these regions was due to the same earth-movements.

The north-western limit of the folds is marked by the great thrust-planes which crop out between Loch Eireboll and Loch Alsh. West of these the Torridon Sandstone is almost horizontal, and the Cambrian beds have a low and regular dip. But upon the thrust-planes the folded rocks have been pushed over the edges of the unfolded beds. Both the folding and the overthrusting were produced by the same forces, and belong to the same series of earth-movements.

The Old Red Sandstone of the Cheviots rests unconformably upon the folded Silurian rocks of the Southern Uplands, and the folding of the latter must therefore be earlier than the deposition of the former. Generally, in fact, north of a line drawn eastwards from the mouth of the Shannon, wherever the folding is most intense the Old Red Sandstone is not involved. Nevertheless, in the Midland Valley of Scotland and in the Cheviot area the Lower Old Red Sandstone was to some extent affected, and the upper division of the system rests unconformably upon it. We may conclude that the most violent folding took place at the close of the Silurian period, but that the earth-movements continued with diminished intensity to the middle of the Devonian period. It is probable that the Grampian fault, which lies along the southern margin of the Highlands, and also the fault that separates the Scottish Lowlands from the Southern Uplands, were initiated during this period

The effect of this great crumpling of the earth's crust was to raise a series of mountain-chains upon the southern border of the north-western continent. They extended from Ireland to Norway, and have been called the 'Caledonian Range.' Arms of the sea were isolated by these mountain-chains, and thus the north-west of Europe became a continental area, bearing upon its surface sheets of water, in which the Old Red Sandstone was deposited. But the continent did not extend south of the Bristol Channel, and in this direction lay the open sea.

The Second Marine Period.—In Carboniferous times the southern sea again spread over the margin of the northern continent; but it was only for a short time that it reached as far as Scotland. Where it entered the Old Red Sandstone lakes, as in the Welsh and Cheviot areas and in the Scottish Lowlands, deposition was continuous; but where it overflowed the old land surface, the Carboniferous beds rest with marked unconformity upon the older rocks, as for example in North Wales and the Pennine Chain.

The Third Continental Period.—In England the second marine period was of short duration. Rapidly the sea grew shallow; and when the Coal Measures were laid down, the whole of our area was land once more, occasionally flooded for a short time by the sea.

At the close of the Carboniferous period the deposits were for the second time crushed against the northern land, and another great system of folds was formed south of the remains of the Old Caledonian range. The new folds run in general from west to east, and they affect the Carboniferous and older rocks of the south of Ireland, the south of Wales, the Mendip Hills, Devonshire and Cornwall, and may be followed into Belgium, Germany and even to the Donetz in Russia. In England the intensity of the folding and of the resulting cleavage is most conspicuously shown in the Devonian and Culm of Devonshire and Cornwall.

Just as the north-western limit of the Caledonian folds is defined by the thrust-planes of the North-west Highlands, so the northern limit of these later folds is marked by another series of thrusts, which has been carefully examined in South Wales and in Belgium. The southern boundary is not so precisely known, but folds of the same age are met with even in Spain.

Outside the limits of these east-west folds another system of folds was formed which ran from north to south, and in the Malvern range attained a considerable degree of intensity. The Old Red Sandstone and the greater part of the Coal Measures were here involved, but not, apparently, the latest of the coal deposits.

There was also a considerable amount of earth-movement of a broader and more gentle character. To this period belong the Derbyshire anticline, which trends from north to south, and also the anticline which runs obliquely across the Pennine Chain, separating the Durham and Cumberland coal-fields from the Yorkshire and Lancashire basins. The Pennine fault, the Craven fault, and the Bala fault were produced in part by the same earth-movements. The Pennine fault runs from north-north-west to south-south-east along the foot of the Northern Pennines, and has its downthrow on the western side. The Craven fault runs nearly from north-west to south-east beneath the southern slopes of Ingleborough, and its downthrow is upon its southern side. The Bala fault strikes from south-west to north-east across North Wales, passing through Bala Lake. Its downthrow is upon the north.

Movement along the faults in some cases continued into the Triassic period or even later, but the folding was for the most part completed and the folds denuded before the Permian beds were laid down, with the result that there is a strongly marked unconformity at the base of the Permian system. But the area of the Permian is limited, and where the Trias spreads beyond, the unconformity is at the base of the latter.

As the folding at the close of the Silurian period raised the Caledonian mountain-range, so the folding at the end of the Carboniferous period caused the elevation of a series of mountain-arcs, which stretched from the south of Ireland eastwards across the middle of Europe. Collectively they formed a range to which the name Hercynian has been applied.

Arms of the sea were again cut off and became salt lakes upon the surface of a northern continent, and in these lakes the Permian and Triassic beds were in part laid down. The mountain-range upon the south intercepted the rain-bearing winds from the southern sea, and thus the continent became a desert; just as Tibet is now a desert because the Himalayas obstruct the passage of the south-west monsoon.

The Third Marine Period.—Once more the sea spread northwards; and the marine Rhætic deposits follow conformably upon the Keuper marls, and are themselves overlaid conformably by the Jurassic beds. In the Mendips and the south of Wales, the latter occasionally overlap the Trias and lie unconformably upon the denuded surface of the Hercynian hills. Generally the shore-line lay towards the north of Scotland, for there the deposits are in part at least of estuarine origin. But there were considerable fluctuations. During the epoch of the Lower Oolites, for example, the land must have extended considerably farther south.

The Fourth Continental Period.—In late Jurassic times and in the early part of the Cretaceous period, almost the whole of the British Isles was land. The Purbeck and Wealden of the south of England are of fresh-water or estuarine origin, and it is only in Yorkshire and Lincolnshire that there are any marine deposits of corresponding age. But the land was very different from that of the preceding continental periods. No folding had taken place, and no mountain-chain was raised upon its southern border. There is no evidence of any great accumulation of material on the land itself, and the abundant flora of the Wealden beds shows that a luxuriant vegetation flourished upon its surface.

The Fourth Marine Period.—In the time of the Lower Greensand a fresh incursion of the sea began, and accordingly the Upper Cretaceous spreads far beyond the limits of the Lower. Where it rests upon the Lower Cretaceous, it is conformable; but where it passes beyond and lies upon Jurassic or older beds, there is usually an unconformity at its base. In Dorsetshire, Antrim and the north of Scotland, most of the Upper Cretaceous deposits are more or less sandy, indicating the neighbourhood of the shore; but the Upper Chalk retains much of its usual character, and during its deposition the sea must have attained its greatest extension.

In spite of the unconformity between the Tertiary and the Cretaceous in the south of England, there is no evidence that the surface had been raised above the water in the interval. But it is certain that in Eocene times the area of the sea was much reduced and the land had spread southwards. The basalt-flows of Antrim and the Hebrides, and the leaf-beds associated with them, prove that the north-western part of the British area was land. Even in the south of England the estuarine character assumed by the Reading and Bracklesham beds towards the west indicates that the land lay near, and probably the Eocene sea did not extend much beyond the present chalk escarpment.

The Fifth Continental Period.—The fresh-water nature of most of the Oligocene deposits and the entire absence of any Miocene beds show that once more the northern land extended southwards at least as far as the south of England. Throughout the Mesozoic era, in spite of oscillations of the earth's crust, there had been no great crumpling in any part of Europe. But now a new system of folds was formed and a new range of mountains arose south of the site of the Hercynian chains. This is the Alpine system, and includes the Alps, Carpathians, Balkans, and most of the mountain-chains of Southern Europe.[1] The main line of folding lay far to the south of England; but just as considerable movements took place in front of the Hercynian range,

[1] It is worthy of note that the elevation of this mountain-system resulted in the isolation of arms of the sea, which ultimately became salt lakes. It was in one of these that the great salt deposits of Wieliczka in Galicia were formed. But Great Britain lies outside the region of these Tertiary salt lakes.

so now there was extensive faulting and some folding in front of the Alpine system.

In England the Wealden anticline belongs to this period, and so also do the sharp monoclinal folds of the Isle of Wight and other parts of the Hampshire basin. The monoclines run from west to east, and have a very steep northern limb and a gently sloping southern limb. There is even a certain amount of overthrusting in the northern limb, as has been demonstrated in the Isle of Purbeck.

Of far greater magnitude than these were the earth-movements that occurred in the north-west. The basalt plateaux were broken up and great masses sank several thousand feet. The northern continent was, in fact, destroyed, and the Atlantic spread over a large expanse which in Eocene times was land. Only a few upstanding blocks remain as islands to indicate the former extension of the plateau.

These were the last great changes that occurred in the British area. The fluctuations of the sea during the Pliocene period, and the changes that took place during and after the Glacial age, are, in comparison with them, of small importance. The North Sea and the North Atlantic were now in existence, and before the beginning of the Pliocene period the broad features of the geography of Northern Europe had been determined.

CHAPTER XXXI

THE HISTORY OF IGNEOUS ACTIVITY IN THE BRITISH ISLES

In the preceding chapter it has been shown that the geological history of the British Isles can be divided up into an alternation of continental and marine periods, and that the succession and duration of these periods are determined by the distribution in time of the major disturbances of the earth's crust. Now it is one of the fundamental principles of modern geology that igneous activity is closely dependent on earth movement. Consequently it follows that the periods of uplift and erosion are in the main also the periods of eruption and intrusion of igneous rocks. As will be seen later, there was one important exception to this, in the Ordovician, but in the other cases the rule holds good.

In the case of the larger periods of igneous activity the sequence of events is in general as follows: (1) eruption of lavas and ashes from vents or fissures; (2) intrusion of plutonic masses in depth; (3) the phase of minor intrusions, dykes, and sills. This order is exemplified by most of the British occurrences, though in some instances the evidences of the volcanic phase have been removed by denudation, while the intrusions remain.

If we consider the igneous history of the British Isles as a whole, we find five great periods of activity, of varying duration. In the case of four of these the maximum coincides with the four chief periods of folding and uplift, while one is anomalous, and occurs in the middle of the first marine period. The table on p. 493 shows the relations of the different geological systems to the periods of folding and eruptivity:—

Pre-Cambrian.—The Lewisian gneisses of the north-west Highlands, and their probable equivalents in other parts of the country, consist of an enormous but unknown thickness of igneous rocks, which were undoubtedly formed at a great depth, since they are plutonic in character, with later dyke intrusions: the presence of lava pebbles in the Torridon sandstone shows that a volcanic phase once existed, but the products of it have been removed by denudation. The plutonic rocks show a wide variety of composition, ranging from granite, through diorite and gabbro, to ultrabasic: that is to say, they form an example of a subalkaline plutonic complex on a vast scale. After intrusion they were strongly compressed by folds striking N.W.–S.E., and invaded by innumerable basic dykes having the same direction. The

	Character.	Name of Fold System.	Strike of Folds.	
Pleistocene, Pliocene .., Miocene .., Oligocene .., Eocene ..	4th continental	Alpine	E.–W.	Basalt plateau of Skye, Mull, Antrim. Plutonics of Cuillins, Rum, Mull, Arran, Mourne Mts. [Carrock Fell, Rowley, Clee Hills, &c.]
Cretaceous, Jurassic ..	3rd marine	—	—	—
Trias .., Permian .., Upper Carb.	3rd continental	Armorican-Pennine	E.–W. N.–S.	Exeter Lavas. Granites of Devon and Cornwall. Whin Sill. Derbyshire toadstones and dolerites.
Lower Carb.	2nd marine	—	—	Basalts of Central Scotland.
Upper O.R.S., Lower O.R.S.	2nd continental	Caledonian	N.E.–S.W.	Lavas of Glencoe, Ochils, and Sidlaws, Cheviots. Newer Granites of Highlands, Galloway, Lake District, Donegal, Down, Leinster.
Silurian .., Ordovician, Cambrian ..	1st marine	—	—	Lavas of Wales, Lake District, Salop, S. Scotland. Intrusion of plugs of N. Wales, Ennerdale. Assynt complex.
Torridonian	1st continental	—	—	Volcanics of Wales and Midlands.
Lewisian	Unknown	Huronian	N.W.–S.E.	Plutonic complex of Lewisian Gneiss, Malvern. Older granites of Highlands. Lizard, Anglesey.

so-called ‘older granites’ of the central and south-eastern Highlands, which are also gneissose, may be in whole or in part of the same age.

Gneissose plutonic rocks very similar to the Lewisian gneisses are also known in Anglesey, in the Wrekin in Shropshire, in the Malvern

Hills, and at the Lizard in Cornwall. The first three are undoubtedly pre-Cambrian, and consist mainly of granitic and dioritic gneisses. The rocks of the Lizard are mainly basic, consisting chiefly of gabbro and serpentine, with a comparatively small proportion of granite. The pre-Cambrian age of these rocks cannot be demonstrated with certainty. In both North and South Wales, and in the Midlands, at Carnarvon and Llanberis, St. David's, in Shropshire on both sides of the Longmynd, at Nuneaton, and in Charnwood Forest, Leicestershire, we find a development of the volcanic phase of pre-Cambrian eruptivity, chiefly in the form of acid and intermediate lavas and ashes; rhyolites, devitrified obsidians and andesites, all much altered. The augite granophyres of Leicestershire are intrusive into these, and therefore later. The relation of the volcanic rocks to the pre-Cambrian sediments and to the Lewisian gneiss is still obscure, but they are almost certainly later than the last-named.

Ordovician.—As before stated, this phase of igneous activity is anomalous, in that it occurs in the middle of a marine period. Consequently its products for the most part take the form of submarine lavas and fragmental rocks; but some intrusions are also assigned to this age. Volcanic activity was most strongly developed in North Wales, extending into Shropshire and in the Lake District. In these two areas, according to the latest views, most of the lavas and ashes are of Llandeilo age, with local beginnings in the Arenig and extensions into the Caradoc and the Ashgill series. In North Wales the chief developments are in the Arenig and Berwyn Hills, Cader Idris, and especially in the Snowdon district. Here are found a great thickness of acid and intermediatelavas and ashes; mainly andesites and dacites on the south and east sides, and rhyolites to the north-west, with corresponding ashes. In Carnarvonshire numerous more or less circular plugs of rock of more plutonic character indicate the vents from which the volcanic material was ejected. Volcanic rocks of very similar character occur in the Shelve district of Shropshire, and in South Wales, especially in Pembrokeshire.

In the Lake District the whole of the Llandeilo series is represented by an enormous thickness, possibly 30,000 feet, of lavas and ashes, mainly andesitic, but with some basalt near the base and rhyolite at the top, extending into the overlying Coniston Limestone series. The intrusive phase of this episode is probably represented by the Ennerdale granophyre, and one or two other masses of semi-plutonic type. There are also some large acid dykes, as at Armboth Fell, and small ultrabasic intrusions in the Skiddaw district (hornblende-picrite), besides numerous basic dykes and sills in many places.

In the Assynt district in North-West Scotland, near the line of the Moine Thrust, is a series of plutonic rocks older than the thrust, but intrusive into the Cambrian: therefore presumably of Ordovician or

Silurian age. These are unique in Britain, as they are all of very well-marked alkaline character, including quartz-syenite, syenite, nepheline-syenite, and peculiar types known as borolanite and ledmorite. These form a well-marked plutonic complex, and show considerable resemblance to the Devonian intrusions of Kristiania.

The Caledonian Igneous Rocks.—The great Caledonian system of folding, which was of so much importance in determining the structure of Scotland, Northern England, Wales, and Ireland, began towards the end of Silurian times, reached its climax in the Old Red Sandstone, and in Scotland, at any rate, its igneous effects continued into the Carboniferous and probably even, locally, to the Permian. Almost everywhere the folding was accompanied by eruption and intrusion of igneous rocks. In Scotland the earliest phase was the intrusion in many parts of the Highlands of a great series of plutonic rocks, known collectively as the 'Younger Granites.' This is a somewhat unfortunate term, since both in Western Scotland and in Ireland there are still younger granites, of Tertiary date, as described in a later section. In the Highlands three principal groups may be recognised, as follows: (1) Caithness and Sutherland; these range from acid to ultrabasic, but hornblende granites are dominant, such as those of the Ord of Caithness, Beinn Laoghal, and Lairg. (2) Aberdeen and the Cairngorm Mountains: these include some very large masses of muscovite-biotite granite and biotite granite at Peterhead, Aberdeen, Lochnagar, and Cairngorm, with smaller masses of quartz-diorite, diorite, gabbro, norite, and troctolite; these basic types are best seen at Ellon and Belhelvie, Aberdeenshire. Small masses of granite and quartz-diorite are scattered about the counties of Banff, Nairn, and North-Eastern Inverness. (3) The Western Highlands; here the dominant types are biotite granite, hornblende granite and tonalite, as in the great bosses of the Moor of Rannoch, Loch Etive, Ballachulish, and Ben Nevis; the kentallenite (olivine-monzonite) of Kentallen, near Ballachulish, is a rare type. The red granite of the Ross of Mull probably belongs here.

In the extreme south-west of Scotland, in Galloway, three large bosses of granite, at Criffel, Dalbeattie, and the Cairnsmuir of Fleet, and some smaller ones, are intrusive into Silurian sediments: they range in composition from muscovite granite to hornblende granite and tonalite; there are also many dykes. The augite granite of the Cheviot Hills also belongs to the Old Red Sandstone period. Viewing the newer granites of Scotland as a whole, it appears that they become progressively slightly younger towards the south, ranging from latest Silurian to Middle Old Red Sandstone.

In the Lake District there are three principal granite masses, those of Skiddaw, Shap, and Eskdale, and several minor intrusions of this age. The Skiddaw granite, a grey muscovite-biotite granite, with a peculiar patch of greisen at one point (Grainsgill), is intrusive along the principal axis of an anticline of Devonian age. It is significant that the line of this anticline, when continued, passes close to the very similar granites of the Isle of Man and Leinster; these are possibly all connected underground. The Shap granite forms an oval plug about 1½ miles by 1 mile, and is perhaps the neck of an enormous volcano. It cuts through Silurian rocks, and pebbles of it are found in the basal Carboniferous conglomerate: it is therefore Devonian. The Eskdale intrusion is a large mass, about 12 miles long, of grey or pink muscovite-biotite granite: its form appears to be related to the Devonian folding and thrusting movements. Both the Shap and Eskdale granites are accompanied by many dykes.

In Ireland the granites of Newry in County Down show a very strong resemblance to those of Galloway, and are no doubt contemporaneous with them. In Donegal, Sligo, Mayo, and Galway are several large masses, parts of which at any rate are probably Caledonian, though some may be comparable to the 'Older Granites' of Scotland. In Leinster is an immense bathylithic mass of muscovite-biotite granite 70 miles long at the surface, and with probably much greater extent underground.

The copper-lead-zinc veins of the Lead Hills in Southern Scotland, of the Lake District, of Shropshire, and of North and Central Wales, which lie in Ordovician and Silurian rocks, seem to belong to this age. There is also a little gold in veins around Dolgelly.

Turning now to the extrusive rocks of the Caledonian series, we find andesitic lavas in the Glencoe district in Argyllshire, and a very large development of Old Red Sandstone lavas in the Ochil and Sidlaw Hills in Perth and Forfar, in the district south-west of Edinburgh, and in the Cheviot Hills. These are mostly andesites, and are accompanied by numerous small intrusions of quartz-porphyry and porphyrite. In Scotland volcanic activity remained in full swing into the Lower Carboniferous, giving rise to great outpourings of basalt as plateau eruptions in the central valley, especially in Stirling, Dumbarton, Renfrew, and Lanark, and in Haddington (Garlton plateau). The latest stages were marked by many small volcanoes of the puy type, yielding basalt and even ultrabasic lavas. These form an immense number of necks and plugs scattered about the country, and in Fife eruptivity seems to have gone on into the Permian. The gradual change from intermediate to basic and ultrabasic lavas is noteworthy. There were also in the Carboniferous some intrusions of distinctly alkaline rocks, including trachyte and teschenite, as necks and sills, as in the Eildon Hills, Traprain Law, Bass Rock, and Car Craig.

The Armorican-Pennine Igneous Rocks.—In this system the axes of the folds run approximately E.-W. in the southern parts of England, Wales, and Ireland, and N.–S. in the north (Pennine anticline). The most important igneous activity manifested itself in Devon and Cornwall, where great masses of muscovite-biotite granite are intruded into the highly-folded older rocks up to the Carboniferous. There are five chief granite masses at the surface and several smaller ones, all being probably subsidiary domes on the top of a great bathylith. All the masses are very similar, and are characterised by conspicuous pneumatolytic effects, with development of tourmaline and abundant ores of tin, tungsten, copper, arsenic, lead, and zinc, associated with pegmatite, aplite, greisen, and quartz porphyry dykes (elvans). This is one of the most richly mineralised areas in the world.

In the northern area we find lavas (toadstones) and dolerite intrusions in the Lower Carboniferous rocks in Derbyshire, and farther north the Great Whin Sill, an enstatite-dolerite, is intrusive into the Lower Carboniferous over an area of many hundreds of square miles, but these may perhaps be connected with the latest phases of the Caledonian disturbances. Connected with the igneous activity, doubtless, is the extensive occurrence of ores of lead and zinc, with fluorspar and barytes, in Flint and Denbigh, Derbyshire, West Yorkshire, Westmorland, Cumberland, Durham, and Northumberland, the ores lying in the Carboniferous limestone.

It should be noted that the Armorican vulcanicity of England partly overlapped in time the Caledonian vulcanicity in Scotland: though contemporaneous, these two phenomena were due to different sets of movements, and affected different areas.

The Tertiary Igneous Rocks.—The important and interesting eruptions and intrusions that took place in North-Western Britain during the Eocene period must be regarded as a sort of far-off echo of the disturbances that shook Southern and Central Europe, and led to the formation of the great Alpine mountain chains; but the movements themselves were for the most part of quite different character, being mainly simple faulting and block-subsidence, with occasional local folding accompanying explosive outbursts on a small scale (see also p. 226). The chief areas where igneous rocks of this age are now found are in Skye, Rum, and some neighbouring smaller islands, Mull, Ardnamurchan, Arran, and Antrim, and the Mourne Mountains in Ireland. In most of these areas the general succession of events was first the outpouring of great sheets of basalt as fissure-eruptions; at a later date differentiated plutonic rocks were intruded into and under the basalts of the plateaux, followed by a phase of sills and dykes, also differentiated to some extent. The best known area, that of Skye, has already been described in some detail (see p. 248). Here the full sequence is very clearly seen. In the other Scotch areas the phenomena are very similar, though not yet described in such detail. In the plutonic phase the Isle of Rum shows a remarkably fine development of ultra-basic rocks rich in anorthite felspar: in Mull and other areas this stage consists of gabbro and granophyre, while in Arran the great granite boss of Goatfell is conspicuous. In North-Eastern Ireland the plateau basalts cover an enormous area, and in County Down are the large biotite-granite mass of the Mourne Mountains and gabbro-granophyre complex of Carlingford. A remarkable feature of Southern Scotland and Northern England are the great andesite or basalt dykes, which seem to radiate from Arran. One of them nearly reaches the Yorkshire Coast, and several are seen in the Northumberland coal-field.

There are in various parts of England a certain number of igneous rock-masses whose age cannot be definitely proved, but which are believed for various reasons to be Tertiary. Of these we may mention the gabbro and granophyre of Carrock Fell, Cumberland, which strongly resemble the Tertiary plutonics of Ardnamurchan, Mull, and Carlingford; in South Staffordshire also, the Swinnerton dyke, which cuts the Trias, is very like the Tertiary dykes of Scotland, and it is quite possible that some of the basic dykes of the Lake District and North Wales may belong to this period. Finally, there are in the Midlands, as at Rowley Regis and Pouk Hill, near Walsall, and the Clee Hills in Shropshire, certain intrusions of a peculiar type of analcime-dolerite which are believed by many petrologists to be of Tertiary age, although there is no absolute proof of this.

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