A TEXT-BOOK OF GEOLOGY:

FOR USE IN MINING SCHOOLS, COLLEGES, AND SECONDARY SCHOOLS.

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BY

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PREFACE.

This volume comprises a systematic course of lectures carefully revised and expanded so as to cover the requirements in Geology as now defined for Engineering, Mining, and Agricultural Schools and Colleges.

The first principles of Geology are, so to speak, the ABC of the science. They are mostly based on the simple processes that are now going on around us; and when we know Man we are able to read the story of the earth wherever we may chance to find ourselves. But the student who confines his observations and studies to his own immediate neighbourhood is in danger of acquiring a false sense of proportion, and may in time unconsciously come to believe that the things and processes he sees in his own terrain are typical of the whole globe. When he afterwards comes to travel further afield he may find himself compelled to modify his standards and renounce many of his early conceptions. The corrective of local prejudices and a narrow horizon is extensive reading and still more extensive travel.

A word to the student. Make an early acquaintance with the facts of geology as presented in the field. Miss no chance of travel or exploration with the experienced geologist. Cultivate the faculty of exact observation, and be mindful not to form hasty conclusions. Remember that things are not always what they seem. Make extensive collections of rocks and fossils, and be careful to keep the fossils of each horizon apart. Take every care to preserve your fossils from injury. The dictum of the Hon. Walter Mantell that "a fossil that is worth collecting is worth its paper" is as true now as when made to the Author forty years ago, and applies equally well to rock specimens. Do not attempt to describe new species; leave that to the specialist. Even when you have gained some note as a writer on geology, refrain from coining new terms.

The scientific study of scenery is one of the most fascinating branches of geology. It embraces the morphological description of the surface features, and the investigation of the causes which have brought these forms about. To be successful in diagnosis you need to be equipped with a good knowledge of geological causation. In the review of the topography of a given terrain, always bear in mind that every natural feature is the result of some definite happening or combination of happenings. Take the familiar crags and hollows, peaks and valleys, headlands and bays. These owe their existence for the most part to the relative hardness of the rocks in which they are carved. Here, again, beware of forming hasty conclusions, and remember that circumstances may alter cases. Coastal embayments are not invariably due to projecting headlands of hard rock. The spacious and beautiful Golden Bay in North Nelson, New Zealand, is guarded on one side by a narrow barrier of loose sand twenty miles long, against which the fury of the cyclonic gales of the South Pacific beats unavailingly. Long lines of escarpment are not necessarily the result of faulting. Invariably they are the result of uplift of sedimentary strata of varying degrees of hardness, followed by denudation, and the excavation of longitudinal hollows along the softer zones of rock. The mere circumstance that the prominent ridges and peaks of a mountain complex are nearly of uniform height cannot be taken as *primâ facie* evidence that these ridges and peaks are the remnants of an ancient peneplain. When you are tempted to invoke the aid of a dissected peneplain, consider the effect that may be produced when a great succession of sedimentary rocks of alternating hard and soft strata are thrown into a series of isoclinal folds, the arches of which are truncated and cut by deep transverse gorges and wide longitudinal valleys. Since the rocks in each fold were originally uplifted to the same height and offer the same resistance to denudation, the harder bands of rock will obviously form a series of more or less parallel ranges, the prominent peaks of which will stand at about the same height.

Do not select a single specimen of a rock for analysis and regard it as representative of the whole mass, as the results may be altogether misleading. All sedimentary and igneous rocks vary considerably in composition in different parts, the former because they are mechanically formed, the latter on account of the development of large phenocrysts or the proximity of sedimentary or other rocks. Select fresh unweathered examples whenever procurable, and, except it be an analysis of a particular fragment that is required as an aid to microscopical examination, select the average sample or samples with as much laborious care as you would sample a coal-seam or an ore-vein. Unless you are a specialist, which is unlikely, do not attempt the analysis of your rock samples ; do not think that because you have waded through the analysis of a rock specimen or two in your graduate course that you are competent to undertake the systematic analysis of a rock.

Rock analysis is work calling for special skill and great experience. But the greatest skill in the laboratory may be stultified by negligent sampling in the field ; and, conversely, the most painstaking work in the field may be rendered worthless by lack of experience in the laboratory.

I desire to acknowledge my indebtedness to the Director of the Geological Survey of the United States for permission to utilise the illustrations of the Survey's publications, a privilege of which I have fully availed myself ; to Dr Tempest Anderson for the use of Plate XVI. and Figure 123 ; to Mr E. F. Pittman, Government Geologist for New South Wales, for the use of Plate XXXVIIIA. ; and to my Publishers, who have courteously placed at my disposal many of the figures scattered throughout the text, as well as the beautiful plates of fossils illustrating Chapters XXII. to XXXIII.

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A TEXT-BOOK OF GEOLOGY.

PART I.

CHAPTER I.

SOME FIRST PRINCIPLES.

Before proceeding with the detailed study of the crust of the Earth and the processes which have modified its surface, it is necessary as a first step to take a bird's-eye view of the whole history of the globe from its first beginning up to the present time. By pursuing this course we shall acquire a better understanding of the facts subsequently presented ; for it is obvious that when the ground-plan of the structure, so to speak, has been reviewed and intelligently grasped, the filling in of the details will be a matter of comparative ease.

The Earth when viewed in its widest sense is found to consist of three concentric envelopes, namely (1) the *Atmosphere* ;[1] (2) the *Hydrosphere* ;[2] and (3) the *Lithosphere*.[3]

The *Atmosphere* is the outer gaseous envelope, the *Hydrosphere* the watery envelope, and the *Lithosphere* the solid rocky crust on which we live.

The central core enclosed by the Lithosphere is called the *Barysphere*[4] from its supposed greater density.

The *water-surface* of the globe comprises about 145 million square miles, and the *land-surface* about 52 million square miles.

GENERAL OUTLINE OF GEOLOGICAL HISTORY.

The Purpose of Geology.—Geology is the science which deals with the materials forming the crust or outer shell of the globe.

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[1] Gr. *atmos* = vapour, and *sphaira* = a sphere.
[2] Gr. *hudor* = water, and *sphaira*.
[3] Gr. *lithos* = a stone, and *sphaira*.
[4] Gr. *barus* = heavy, and *sphaira*.

It is thus a science of observation with a laboratory embracing the open field and mountain slope, the river-valley and rocky strand.

From a study of the conditions that govern the deposition or formation of sediments in our existing seas and lakes, and from a knowledge of the habits and environment of the animals and plants that now people and clothe the Earth, the geologist attempts to follow the orderly succession of the conditions that existed in bygone ages. For the construction of this mental picture he mainly relies on the structure and composition of the rocks, and on the fossil remains of the plants and animals which the rocks enclose.

In other words, the geologist applies the present to read the past, and in doing so he is surely on safe ground, for the present is merely a continuance of the past. He recognises that the same air and the same precipitation of watery vapour in the form of rain have existed since the beginning of geological time, that water in the form of running streams has always played a dominant *rôle* in wearing away the solid land, and that seas and lakes as occupying the hollows and depressions have always, as now, been the places where the rocky detritus carried down by the streams has been sorted and spread out.

The Origin of the Earth.—The Earth is a planet belonging to our solar system. From the researches of the astronomer we learn that many of the so-called fixed stars are suns, each moving in its own orbit, and each, like our own Sun, attended by a system of dark satellites or planets.

An investigation of the heavenly bodies has shown that some exist in the form of intensely heated incandescent gases, some as globular masses of highly heated glowing liquid matter, and others, like our own Earth, as dark solid bodies. According to the *nebular hypothesis*, it is believed that the solid bodies were at one time masses of incandescent gases, and that they became first liquid and then solid through the radiation of their heat into space.

When the heated globular body had become sufficiently cool, a solid crust, at first thin and brittle, formed on the surface. As the loss of heat continued, the glassy crust became thicker and thicker, and in its endeavours to adapt itself to the shrinking dimensions of the molten interior mass, became wrinkled into ridges and valleys, like the skin of a dried-up apple.

It is almost certain that through the cracks and fissures thus formed, floods of uprising molten matter would be spread over the thin crust, portions of which would, from this cause, collapse and become engulfed, leaving pools and lakes of liquid magma over which a new crust would gradually form.

In course of time the scarred and gnarled igneous crust became cool enough to permit the condensation of the watery vapours that enveloped the Earth. A portion of the waters settled in the hollows and formed the first seas and lakes that ever existed on the face of the globe; while another portion penetrated the dry land, thereby forming the springs from which the first streams and rivers took their source.

The restless waters of the new-born seas at once began to wear away the dry land along their shores, and the streams draining the valleys to deepen and widen their channels. The denuded material was spread out in layers and beds on the rocky floor of the seas, thus marking the beginning of the conditions of sedimentation that have prevailed without interruption up to the present day.

It was not until the precipitation of the dense aqueous vapours had taken place and the waters were gathered together into seas that life appeared on the globe.

Beginning of Geological Time.—Geological time dates back to the first beginning of the physical conditions that now prevail upon the Earth; that is, to the time when detrital matter derived from the denudation of the dry land first began to be spread out in the form of beds or layers on the floor of the new-born seas and lakes. These ancient sediments formed the first records of geological time.

The Action of Water in Destroying and Re-forming.—From that date up till now, water has continued to be the most powerful agency in sculpturing and modifying the surface of the Earth. In wasting and eroding the dry land, in transporting the eroded material, in sorting and spreading it out, the action of water has been unceasing throughout all time up to the present day.

The amount of matter forming the Earth is practically a fixed quantity; hence it is obvious that all the deposits and beds now exposed in the dry land must have been derived from the destruction of the first igneous crust, or of sedimentary rocks of later date.

Ever since the beginning of geological time the dry land has been denuded by water, yielding the material to form new deposits in seas and lakes. Through the progressive crumpling of the crust these deposits in course of time became raised above sea-level, forming dry land which, in its turn, was subjected to the agents of erosion, thus yielding material to form newer deposits or strata. This action is still going on, the older formations providing the material for the younger.

From this it will be seen that the same material has appeared re-sorted in different forms, in different geological ages. It is now easy to understand how some of the older formations have been entirely removed by this everlasting denudation, or are represented only by isolated remnants of small extent.

No portion of the original igneous crust, or even of the first-formed sediments, has ever been found; but shreds and patches may still exist, buried beneath the deposits of later times.

The Ocean Basin not Permanent.—The existing dry land of the globe is found to be mainly composed of aqueous or sedimentary rocks, from which it is known that the present distribution of land and water is not that which always existed. On the contrary, by slow movements of the crust extending over countless ages, known to geologists as *secular movements*, some portions of the crust have been elevated, while others have been depressed or submerged. In this way the seas and dry land have been changing places, so to speak, all through geological time; the effect of this wandering of the seas has been to cover the whole of the first igneous crust of the Earth with sedimentary rocks.

The bulk of the sedimentary formations were formed on the floor of the sea, but strata containing freshwater shells and fishes, and sometimes beds of rock-salt, tell us of the former existence of continents, inland lakes, and mediterranean seas of which no vestige now remains. From a study of the rock-formations and the fossils which they enclose, much may be gleaned of the physical geography and life of past geological times.

The Earth's Crust mostly Sedimentary.—An examination of the fabric of the outer shell shows that it is principally composed of stratified rocks—that is, rocks occurring in parallel beds or layers. A study of the materials forming these rocks, and of their fossil contents, shows us that they have been formed by the gradual deposit of sediments on the floor of some sea or lake, or in some cases by precipitation from solutions, or in others by the growth and accumulation of animal or vegetable organisms.

The physical structure of sedimentary or aqueous rocks—as they are sometimes called—is dependent on three main factors, namely:

(1) The *texture* of the material.
(2) The character of the *cementing medium*.
(3) The amount of *induration*, *alteration*, or *metamorphism* to which the material has been subjected.

The term *texture* refers to the coarseness or fineness of the constituent grains or pebbles.

Streams and rivulets, as well as the ebbing and flowing tide of the sea, have through all the ages possessed the same eroding, transporting, and sorting power, and what we now see going on in our valleys and along our shores is a fair example of what took place in earliest geological time.

The denudation or wearing away of the dry land was mainly the work of running water, while the sorting and spreading out of the denuded material was effected by the laving action of the waves of the sea as they advanced and retreated on the ancient strands.

The gravels were piled along the shore in the shallow water; the smaller pebbles were carried into deeper water; while the sands and finer particles were borne further seaward, the latter forming beds of mud at the extreme limit of the deposit.

The gravels along the sea littoral, when consolidated, formed what are termed *conglomerates*; the water-borne sands formed *sandstones*; the more distant muds became *mudstones* and *shales*; while the shell-banks and coral reefs became *limestones*.

Folding and Tilting of Sedimentaries.—The older sedimentary strata have been of necessity subject to all the later movements that have affected the crust of the Earth. They have been indurated by the great weight of superincumbent strata, and plicated or corrugated by entanglement in great crustal folds. Hence the strata do not always occupy the horizontal position in which they were originally laid down, but are inclined or tilted at various angles, being arranged in folds with gentle or steep slopes.

Alteration of Sedimentaries.—Many of the older rocks have been altered or metamorphosed by the rearrangement of their constituent minerals. Thus limestones have been changed to marbles, sandstones to quartzite, mudstones and shales to slates and schists.

The agencies principally concerned in the metamorphism of sedimentary rocks have been pressure, which induces the schistose and slaty structures; heat and circulating waters, which cause a re-arrangement of the constituents, whereby a crystalline structure may be formed. Hence *metamorphic* rocks are often spoken of as *schistose* or *crystalline*.

Origin of Igneous Rocks.—Throughout all geological time the outer crust or shell of the Earth has been subject to the intrusion and overflow of molten *magmas* from below.

Whether the interior is in (*a*) a molten state, or (*b*) exists in a highly heated, but enormously compressed, condition ready to assume the liquid form whenever and wherever the stress is relieved, or (*c*) whether the lavas that are from time to time erupted come from huge subterranean caverns of molten rock that have escaped the general cooling of the crust, is at present not known to geologists.

Notwithstanding the frequency and violence of igneous intrusions in past times, the fact remains that probably nine-tenths of the rocks forming the known crust of the Earth are of sedimentary or aqueous origin.

Rôle of Igneous Intrusions.—Although subordinate in extent and mass, the eruptive rocks have played an important part in the occurrence and distribution of ore-bodies and mineral deposits. Not only are they metalliferous themselves, but in many cases their intrusion has caused a fracturing of the rocks which they penetrated, thus permitting the invasion of the fissured country by metalliferous gases and waters that emanated from the intruding mass itself.

Thus we find that the igneous intrusion frequently played a double *rôle* in the formation of ores :—

(*a*) By fracturing and fissuring the rocks.
(*b*) By supplying the metalliferous gases and waters which deposited their mineral contents in the fissures.

Intrusive igneous rocks have also played an important part in folding, crumpling, and tilting the sedimentary strata which they have broken through, or with which they have come in contact. Moreover, in many parts of the globe volcanic flows and fragmentary ejecta have been piled up so as to form mountain-chains or isolated mountains that frequently attain a great height.

Alteration of Igneous Rocks.—All igneous rocks, like sedimentaries, are subject to alteration. Superheated steam has frequently caused a rearrangement of the constituents ; while the circulation of thermal waters has led to the elimination or removal of some constituents and the substitution of others which are thus *secondary*. It is also found that intense pressure may cause altered lavas and tuffs to assume a schistose structure not unlike that induced in metamorphosed sedimentary rocks.

Interior of the Earth.—Of the interior condition of the globe almost nothing is known, except that the density is greater, and that the temperature increases with the depth, although not at a uniform rate in different places.

The mean density or specific gravity of the whole globe has been determined to be about 5·5, and that of the materials forming the outer portion of the crust to which man has access, about 3. The inference to be drawn from this is that the interior or Barysphere must be composed of materials possessing a greater mean density than those forming the outer shell or Lithosphere.

It has been contended by some writers that the interior must possess a nucleus of iron, or of iron alloyed with nickel and other heavy metals.

The Planetismal Hypothesis.—This view of the origin of the Earth as elaborated by Chamberlin and others is merely a modification of the Nebular Hypothesis. It assumes that the great incandescent nebula [1] which originally composed the solar system

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[1] Lat. *Nebula*=a cloud, fog, or mist.

cooled relatively rapidly, the cooled gases taking the form of myriads of solid meteorites to which the name *planetismals*[1] has been applied. Under the influence of gravity the cold meteorites segregated into knots that eventually became the nuclei of the sun, the planets and their satellites. During this aggregation, the meteorites are believed to have bombarded one another with great violence, thereby becoming hot.

The main source of the high temperature of the sun and of the earth before it cooled was not due to the heat generated by the collision of the constituent meteorites, but to the contraction and consolidation of the mass after the meteorites had come into contact.

All solid bodies possess a potential energy proportional to their distance from, or height above, the common centre of gravity of the globular mass to which they belong. Thus a block of stone resting on the edge of a high tower possesses a large store of this *energy of situation*, which it loses as soon as it falls to the ground. The energy is not lost, but merely transformed into heat.

The packing or crowding of a swarm of meteorites under the influence of gravity, which always acts towards the centre of the mass, is accompanied by the generation of great heat. Meteoric matter is a good conductor of heat, and hence the whole mass would soon assume a uniform temperature. As the packing continued, the globular mass would, in time, reach its maximum density, and thereafter gradually became cool by the radiation of heat from its surface.

The *heat of contraction* might not inconceivably be sufficient to melt the materials in the upper layers, but the lower layers would remain solid as the pressure of the superincumbent mass would be sufficient to prevent expansion, without which liquefaction cannot take place.

The more fusible materials in the upper layers, in accordance with the *law of liquation*, would rise to the surface, and in process of time solidify as a stony crust. The tendency of this process of differentiation would be to divide the constituent materials of the Earth into three distinct zones corresponding to the heavy metal, lighter sulphide regulus, and still lighter stony slag formed in a reverberatory furnace.

The central core and regulus form the barysphere; while the stony slag or crust, now modified and re-sorted by the action of subaerial agencies, constitutes the lithosphere or stony envelope.

Age of the Earth.—Lord Kelvin, in the early 'seventies, basing his estimate on the rate of terrestrial radiation, concluded that the age of the Earth did not exceed 400 million years. But the rocky crust of the Earth contains radium, and radium in disintegrating gives off

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[1] Meaning infinitely small planets.

heat. Hence it is contended that the rate of cooling of the globe must be slower than that of a molten globe containing no radium. On these new premises Professor Jolly has advanced the view that the age of the Earth may be perhaps five times greater than Lord Kelvin's estimate.

Succession of Life in Geological Time.—Examination has shown that the earlier strata contain a few indistinct and badly preserved remains of plants and animals of a very primitive type.

Beds or formations higher in the succession are found to contain a larger and more varied assemblage of plant and animal life, many of a highly complex structure, including molluscs, fishes, huge bird-like lizards, saurians, palms, and tree-ferns.

The higher, *i.e.* younger, deposits contain, besides molluscs and fishes, the remains of many mammals which have representatives living at the present time. In other words, there has been a gradual succession of life throughout geological time from the lowly to the more highly organised forms, this succession of life being characterised by a singular persistency of the primitive types.

The Origin of Life.—The problem of the origin of life is still unsolved. We do not know when life first appeared on the Earth nor what form it took. If we are right in our conception of the Earth as a cooling satellite of the Sun, we are probably not far from the truth in believing that when life first appeared the conditions and environment were such as to render its perpetuation difficult and precarious. Perhaps the first ray of life glowed feebly for a time, flickered, died, and became rekindled many score of times before it eventually succeeded in establishing itself in the saline waters gathered in the hollows of the still steaming crust.

The first assemblage of life of which we have any knowledge appeared in the Cambrian epoch. It comprised representatives of most of the great groups of marine invertebrates, and burst on the geological horizon with the suddenness of a meteor in a September sky. From what we now know of biological processes, it is obvious that this highly specialised congeries of life was preceded by a pre-Cambrian ancestry, of which no certain trace has yet been found.

It is probable that the primordial germs of life were tiny nuclei of jelly-like colloidal matter possessing no higher volition than the "Brownian dance" of motes in a beam of sunlight. As time rolled on, the stream of life gradually increased in volume by the continual accession of more and more complex forms, eventually culminating in the advent of man. We can easily conceive that this stately procession of life could only come into existence as the result of increasing food supply, increasing sunshine, wider seas, and more settled climatic conditions.

The primitive forms came into existence when the conditions of life were adverse. As the conditions became more and more propitious, higher and higher forms appeared.

The primitive and higher types are still coeval.

The highly organised forms are more sensitive to climatic and other changes than the hardier Radiolarians and other lowly types. Hence, as the Earth becomes decadent and the conditions of life less and less favourable, the first types to disappear will be those that were the last to come into existence ; and the last to survive will be the simple primordial forms. In other words, life will disappear in the inverse order of its appearance.

Geological Time marked by Distinctive Life.—Close investigation has shown that certain organic forms occur only in certain beds or strata. Such fossils are termed characteristic or distinctive forms. Geologists have taken advantage of these to divide geological time into periods, just as historic time is divided into periods by succeeding dynasties or empires. These periods are purely empirical or artificial, and are merely used for convenience of description and study.

Tetrahedral Hypothesis.[1]—If we examine a terrestrial globe we cannot fail to observe that the great mass of the dry land lies in the Northern Hemisphere, and the greatest expanse of sea in the Southern Hemisphere. Moreover, we shall at once see that the continental units and seas are frequently triangular in shape, the former presenting their bases to the north and tapering to the south.

Further, we shall find that the continents and seas are antipodal or opposite to one another.

The unequal distribution of land in the two Hemispheres, the dominant triangular shape of the geographical units, and the antipodal distribution of the land and seas cannot be set down to mere coincidence or fortuitous happening, but to the operation of well-defined physical laws.

As so clearly demonstrated by Lothian Green, the arrangement of the continental units approximates the shape of the tetrahedron,[2] which is a figure bounded by four triangular planes. The great oceans lie on the flattened or depressed triangular faces of the figure.

Now a sphere is the figure which presents the smallest surface for its volume, and the tetrahedron the greatest.

So long as a globular mass possesses heat it will continue to shrink, and the inner portion, on account of its greater heat, will

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[1] A very clear and graphic exposition of the Planetismal and Tetrahedal hypotheses will be found in *The Making of the Earth*, by Professor J. W. Gregory, F.R.S., Home University Series. Price 1s., London, 1912.

[2] Gr. *Tetra* = four, and *hedra* = a base or plane.

contract more rapidly than the outer rigid shell. As the cooling and internal shrinking proceed, the globular mass will, in time, be encumbered with an excess of surface which will be most easily disposed of by assuming the form of the tetrahedron.

When a metal tube collapses under compressive stress, as may be easily demonstrated in a compression-testing machine, it becomes triquetral, that is, bounded by three concave sides. As viewed in cross-section, each of the three projecting lobes is seen to be opposite a depression.

The antipodal arrangement of the land and seas is the natural corollary of the tetrahedral form assumed by a rotating globular mass.

GEOLOGICAL HISTORY OF EARTH SUMMARISED.

We may summarise the successive stages through which the Earth has passed up to the beginning of the conditions that now prevail as follows :—

(1) In the beginning the Earth was a mass of nebular incandescent gases swinging through space.

(2) Through loss of heat by radiation the gases eventually became condensed into a highly heated viscous globular body.

(3) By continued loss of heat a solid crust formed on the surface of the liquid globe.

(4) In process of time the crust became thicker and thicker, and in its attempts to adapt itself to the smaller dimensions of the rapidly contracting heated interior, became crumpled and wrinkled like the skin of a dried apple.

(5) When the cooling had sufficiently advanced, the aqueous vapours which enveloped the Earth became condensed, and the waters settled on the land, forming streams and rivers which denuded or wore away the rocky crust.

(6) The streams flowed into the hollows or depressions in which were formed the first seas and lakes that ever existed.

(7) The muds, sands, and gravels carried down by the streams were sorted and spread out on the floor and along the strand of the seas, forming aqueous or sedimentary deposits that were thus the first records of geological time.

(8) It was probably soon after streams and seas came into existence that life first appeared on the globe.

(9) Since the beginning of geological time the dry land has always been subject to denudation or erosion by the action of moving water. The formation of aqueous deposits has, therefore, been continuous throughout all geological time in those portions of the globe occupied by seas and

lakes; but as the areas of denudation and deposition have been constantly changing places, deposition has never been continuous in any one area.

(10) Through the slow secular crumpling of the Earth's crust causing elevation in one portion and subsidence in another, the older formations in course of time became dry land, and thus provided the material to form newer and younger formations.

(11) In the continuous cycle of erosion and deposition that has always prevailed, the same material has appeared re-sorted in different forms of aqueous rocks.

(12) Since the beginning of geological time the sedimentary strata which comprise the great bulk of the known crust have been intruded by igneous dykes, or broken through and covered in places with streams of lava and volcanic ash.

(13) The strata originally laid down in a horizontal position have been folded by slow secular crustal movements, and frequently broken, crushed, and tilted at various angles by igneous intrusions.

(14) *Sedimentary* and *igneous* rocks alike are subject to alteration or metamorphism, forming the class of rocks known as *metamorphic*.

(15) The fossil remains enclosed in the rocks show a gradual evolution from the lowly to the more highly organised types now inhabiting the globe, but the primitive forms have been persistent through all time.

(16) The *Nebular Hypothesis* supposes that the Earth was a nebula of incandescent gases, the heat of which gradually radiated into space until the planet became a globular mass of glowing molten matter in which the heavier metallic constituents segregated themselves, under the influence of gravity, into a heavy central core, forming the barysphere; while the lighter material arranged itself as an outer concentric shell constituting the lithosphere.

In course of time the glowing mass cooled sufficiently to allow the outer envelope to form a solid crust. And as the heated interior of the Earth contracted more rapidly than the outside crust, the surface became crumpled and wrinkled in its endeavours to accommodate itself to the rapidly diminishing dimensions of the interior.

When the outer envelope had sufficiently cooled, the aqueous vapours, which up till now covered the surface in a dense impenetrable cloud, became condensed and soon settled in the hollows. Thereafter, the newly-formed seas and the other agents of denudation began the cycle of processes of denudation and re-sorting, destruction, sorting and reconstruction, which have continued without intermission through all the geological ages.

(17) The *Planetismal Hypothesis* assumes that the primeval gaseous nebula of our solar system cooled rapidly and resolved itself into a vast cloud of solid meteorites called planetismals, which, under the operation of gravity, became segregated into knots. The largest knot formed the nucleus of the Sun, the smaller knots, the nuclei of the planets.

The packing and contraction of the meteorites generated sufficient heat to cause the fusion and permit the differentiation of the constituents into a central barysphere and an outer lithosphere.

Thereafter the crumpling, denudation, and re-sorting of the stony crust proceeded as postulated in the nebular hypothesis.

CHAPTER II.

THE SCOPE OF GEOLOGY.

The whole scope of geological investigation is contained in two principal divisions, namely :—

(*a*) General Geology.
(*b*) Economic Geology.

General Geology,[1] with which we are mainly concerned, covers a wide field of scientific research. It deals with the origin and structure of the rocky materials forming the crust of the Earth, with the manner in which the strata are arranged or disposed, and with the agencies which have brought about the present configuration of the surface. It also concerns itself with the chronological succession of the various groups of rocks, and attempts to classify the strata in accordance with their fossil contents.

Economic Geology, also known as **Mining** or **Applied Geology**, is a highly specialised branch of geology that possesses a peculiar interest to the miner and mining engineer. It concerns itself with the origin, mode of occurrence, and classification of mineral deposits of all kinds, and with water supply. Its study is seldom attempted until a knowledge of the fundamental principles of General Geology have first been acquired.

Different Branches of General Geology.—For methodical study General Geology is most conveniently considered under the following subdivisions :—

(*a*) *Petrology*, which deals more particularly with the character and structure of the rocky material forming the crust.
(*b*) *Dynamical Geology*, which investigates the agencies that form, denude, and re-form these materials, as well as the processes which tend to modify or change the shape and configuration of the crust.
(*c*) *Structural Geology*, which concerns itself with the arrangement of the rocky materials.

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[1] Gr. *ge* = the earth, and *logos* = description, discussion.

(*d*) *Palæontology*, which deals with the plant and animal remains embedded in the rocks.

(*e*) *Stratigraphical Geology*, which attempts to unravel the order in which the rocks have appeared, and to interpret the geological history of the globe.

Historical.—As a true science geology dates from the close of the eighteenth century. Before that time there were, even among scientists, many theories relating to the origin of earthquakes, volcanoes, fossils, and other phenomena that to us, with our better knowledge, seem curious and sometimes whimsical.

Among the founders of the science as we now know it, the names of the contemporary workers, Abraham Gottlob Werner, Professor of Mining at Freiberg; James Hutton, M.D., of Edinburgh; and William Smith, an English land-surveyor, stand pre-eminent.

Smith was the first to show by actual field observation that stratified rocks could be identified and arranged in chronological sequence according to their fossil contents. By his epoch-making work on the Jurassic rocks of South-West England, he laid the foundation of Stratigraphical Geology. His famous "Geological Map of England and Wales," published in 1815, was the first attempt to represent the geological relationships of the different rock-formations over an extensive tract of country, and subsequently it became the model of all geological maps.

Werner, a persuasive and eloquent teacher, maintained that the organic remains found in different rock-formations bore a constant relation to the age of the deposits. He affirmed that all rocks above the basal granites, gneisses, and metamorphic rocks were of aqueous origin, including the trap rocks; and this contention formed the cardinal doctrine of the school known as Neptunists.

Hutton recognised the aqueous origin of sandstones, shales, and limestones, and in his philosophical writings forcibly discussed the consolidation, uplift, tilting, and bending of strata. He considered crustal movements as due to extreme heat and expansion supplemented by volcanic disturbance and earthquakes. His views found many disciples and formed the basis of the theses of the school of Vulcanists or Plutonists.

The fundamental truths of geology were subsequently sorted and crystallised by Charles Lyell, a Scotsman, and in 1830–33 embodied in his monumental *Principles of Geology*, which from the first met with extraordinary success and at once placed the author in the front rank of geologists.

CHAPTER III.

THE DENUDATION OF THE LAND.

Denudation Defined.—By *denudation* [1] is meant the wearing away, wasting, or breaking up of the surface, whereby the general level of the land is lowered. It therefore embraces the work of all the agents of wear and tear.

Erosion refers to the more active and obvious wear and tear carried on by the sea, by streams, rivers, and glaciers, and it is embraced within the general term *denudation*.

The principal agents of denudation are :—

(*a*) Air and wind.
(*b*) Rain.
(*c*) Frost.
(*d*) Streams and rivers.
(*e*) Glaciers.
(*f*) The sea.

Denudation that takes place above sea-level is termed *sub-aerial*, and that which takes place below sea-level, *marine*.

In a general way we may say that *air*, *rain*, and *frost* act upon the dry land, decomposing, softening, and breaking up the surface of the rocks. The joint action of these agents is generally spoken of as *weathering*.

The material loosened by weathering gradually finds its way under the influence of gravity to lower and lower levels, until at last it gets within the reach of running water in the form of streams and rivers by which it is transported to the sea.

Scope of Denuding Agents.—Streams and rivers *erode* or cut away the bottom and sides of their channels ; while the sea *erodes* or eats away the edge of the dry land that borders its shores.

The action of air, rain, and frost is silent, slow, and almost imperceptible ; that of rivers and the sea relatively rapid and obvious. The deep river-gorge, the undermined and tumbling sea-cliff, are

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[1] In its literal sense it means to expose, or lay bare, rocks that lie below the surface. This is what prolonged denudation actually does perform. Denude comes from Lat. *de*=down, and *nudus*=naked.

evidences of active erosion that cannot fail to attract the notice of even the most casual rambler among the mountains or on the seashore.

The eroding action of glaciers, like that of air and rain, is silent and perhaps relatively slow; but its effects are nearly always quite obvious in the form of rounded contours, striated, and furrowed rocks.

THE WORK OF AIR.

The atmosphere consists of a mechanical mixture of about four volumes of nitrogen and one volume of oxygen (N79·1,O20·9), with traces of carbon dioxide gas (CO_2), water-vapour, ammonia, ozone, and other gases. The proportion of carbon dioxide is about 3·5 parts in 10,000. The action of the air is *chemical*, *mechanical*, and *physical*. Its chemical activity as a denuding agent is mainly due to certain inherent properties possessed by carbon dioxide and oxygen.

Activity of Carbon Dioxide.—Let us first consider the case of carbon dioxide. This gas, like a lump of sugar, is dissolved by water and water-vapour. Even at ordinary atmospheric pressures water can dissolve its own volume of the gas. Now when water or moist air containing carbonic acid (CO_2,H_2O) comes in contact with a carbonate mineral or a calcareous rock, the carbon dioxide in the water unites with the carbonate of lime in the rock, forming a bicarbonate of lime, which is soluble in water and therefore easily removed.

In this way the surface of a limestone or calcareous sandstone is eaten away; and as you may observe for yourself by examining a limestone cliff or ledge, the grains of sand which are not acted on by the carbonic acid stand up in sharp relief on the surface of the rock, as also do sharks' teeth that may be present.

When a calcareous sandstone is acted on, the removal of the binding medium or cement allows the grains of sand to become free, when they are then easily carried away by the wind, rain, or moving water.

This eating away of the rock is due to chemical solution; hence the term *corrosion* is frequently used to denote *chemical denudation*.

Carbonic acid also acts as a powerful agent in weathering or decomposing all rocks containing silicates of alumina, potash, or soda. Both potash and soda possess a greater liking or affinity for carbon dioxide than for silica, with the result that they combine with carbon-dioxide acid, forming soluble carbonates, thereby liberating the silicate of alumina and other undissolved constituents that may be present.

Perhaps one of the best examples of this mode of rock-decomposition is that seen in the rotting of granite. The three essential constituents of this rock are quartz, felspar, and mica. The felspar is a silicate of alumina and potash. The potash unites with the atmospheric CO_2, forming a soluble carbonate of potash, while the silicate of alumina remains behind to be afterwards washed away by the rain. With one important constituent removed, the surface of the rock crumbles away, liberating the quartz grains and the mica scales, which are then carried away by the wind, rain, or moving objects.

When a rock loses its cohesion by the removal of a constituent, or by the dissolving out of the cementing medium, so that the remaining constituents become liberated or crumble into sand, it is said to be *disintegrated.*

Chemical Work of Oxygen.—*Oxygen* is an active weathering agent, but a less powerful one than carbonic acid. In the case of silicates it frequently begins to act after the carbonic acid has effected the initial decomposition of the mineral. When the silicate mineral contains iron protoxide (FeO), as is frequently the case, the FeO is liberated and unites with the atmospheric oxygen and water, forming the hydrated brown oxide called *limonite,* to which the rusty-brown colour of all weathered rock-surfaces is due.

Oxygen also acts energetically in conjunction with moisture in the decomposition of metallic sulphides that happen to be present in rocks. The most prevalent sulphide is *pyrite* (FeS_2), the disulphide of iron which occurs in all kinds of sedimentary and igneous rocks. This sulphide is oxidised with liberation of sulphuric acid, which at once attacks the aluminous rocks and minerals it comes in contact with, forming sulphates, many of which are soluble in water and hence easily removed. In this way the disintegration of a rock may proceed at a comparatively rapid rate.

THE WORK OF WIND.

Sandhills or Dunes.—Moving air in the form of wind sweeps over the land, carrying before it the particles of dust and sand loosened by the agents of decomposition and disintegration. Along the sea-coast and in deserts, the sands are blown into hummocks and ridges that frequently attain a height of 100 feet or more. Such hummocks and hills of sand are called *dunes* (Plate I.).

Blown sands are frequently piled up in lines of dunes fronting a sandy beach. Where the dunes obstruct the natural drainage to the sea it is not unusual to find chains of shallow lagoons on their inland side running parallel with the coast-line.

In the rainless Sahara and other arid regions there are places where vast accumulations of loose wind-borne sand and dust fill all the depressions and frequently rise to the crests of the ranges. In some parts of tropical Australia, and in the dry belts of Central Otago in New Zealand and the south-west States of America, there are extensive wastes of drifting sand blown by the prevailing winds into continually shifting drifts and ridges.

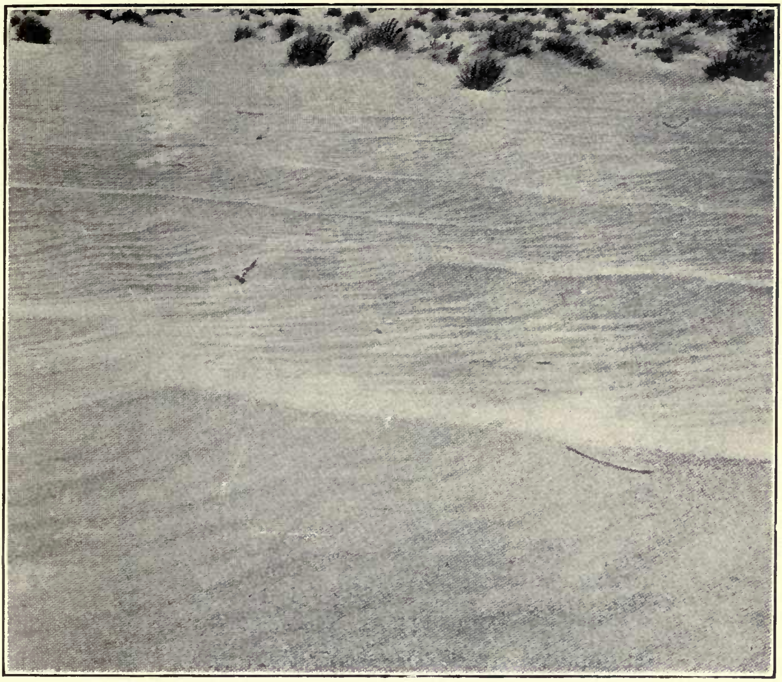
In moist climates the travel of wind-blown sand is relatively slow, and by the planting of sand-binding grasses and shrubs it can frequently be checked; but in arid regions a powerful dust-storm of even short duration, as the author has found, is capable of displacing vast quantities of sand and dust that overwhelm everything in their course. In desert regions the wind is therefore an important sorting and transport agent; but the manner in which it operates is fundamentally different from that of streams and rivers. These always flow in one direction, and hence they carry their load from a higher to a lower level—that is seaward; whereas the desert winds travel backward and forward across the arid wastes, moving the sand and dust from place to place within the arid zone itself. In this way sand may accumulate in desert places until it occupies the whole landscape, thereby creating in the observer's mind the erroneous impression that the denudation of arid regions is excessively rapid.

Sand-Ripples.—Ripples, somewhat similar in appearance to those formed by wave-movement, are frequently formed on dunes by the action of the wind. It has been proved experimentally that ripples are not formed where the sand-grains are of uniform size, but only where there is a mixture of fine and coarse grains. This depends on the principle that where the wind strikes on an obstacle an eddy is formed on its lee-side. Rippling takes place when this eddy in the lee of the larger grains is of sufficient strength to lift the smaller grains.

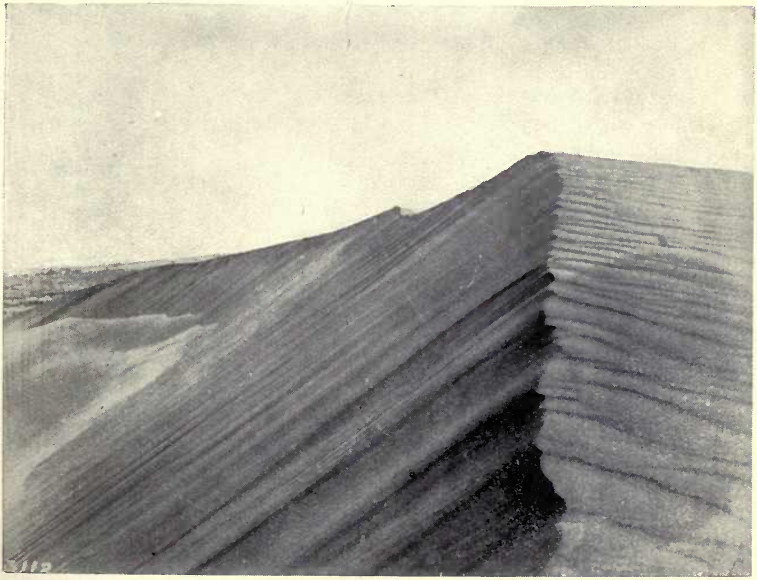
On the windward side of the large grains a long gentle slope is formed, up which the grains travel. At the summit the larger grains are arrested by the eddy and build up the ridge of the ripple, while the vertical motion of the eddy scours out a trough in the loose sand at the foot of the steep slope (Plate I.).

The ripples are continually moving forward, the larger grains falling over the crest of the ridge, thereby assisting to build up the advancing steep lee-slope on which the grains assume the natural angle of rest.

Two series of ripples may be formed in desert regions where the prevailing winds have winnowed out the finer particles, leaving only the coarser sands. The larger or primary ripples occur in parallel lines, and resemble miniature sea-waves. They are formed of the



A. WIND-RIPPLES, PRIMARY AND SECONDARY, IN COARSE SAND.
CROMWELL DUNES. (After Cockayne.)



B. GENERAL VIEW OF WANDERING DUNE, FORMERLY GOOD GRAZING-LAND,
SHOWING RIDGE AT SUMMIT OF SAND-FALL. (After Cockayne.)

coarsest particles such as can only be moved by the strongest winds. The smaller or secondary ripples move forward under the influence of the gentle breezes. They may lie parallel to, or run obliquely across, the trend of the primary sand-waves according to the direction of the wind.

Sand-ripples and sand-waves always lie at right angles to the direction of the wind that produces them.

Mechanical Effects of Wind.—The erosive effects of wind-borne sand is everywhere present in arid regions. The fretting or abrading action of the travelling sand produces effects resembling those of a giant sand-blast. The sand wears away the rough edges of all the rock hummocks that lie in the path of the prevailing winds. Rock-faces are grooved and corrugated, or worn into fantastic shapes according to the varying hardness and resistance offered by different portions of the rock. In some situations, cliffs and stacks are undercut; and in places where wind eddies are formed, miniature cirques and rock-basins may be eroded by the swirling sands (Plates II. and III.).

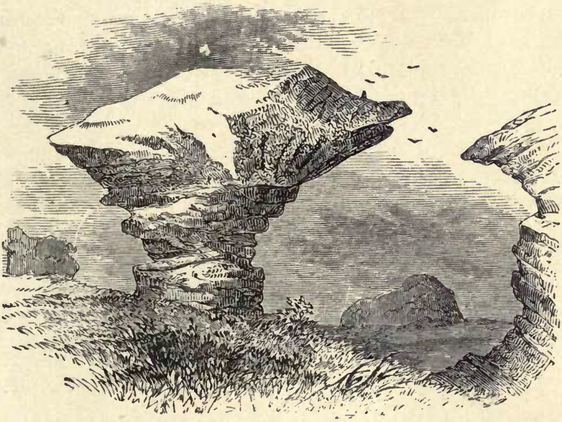


FIG. 1.—Showing sand-worn, mushroom-shaped rock of millstone-grit, Yorkshire. (After Phillips.)

Notable examples of the erosive effects of travelling sand may be seen in Lower Egypt, Western Arabia, on the Great Western Plateau of Australia, and in Southern California.

The sand-erosion suffered by the Sphinx and some ruined temples in Egypt would tend to show that the action of moving sand is relatively rapid.

In places where pebbles lie on a wind-swept rocky platform, the pebbles in time become worn into tent-shaped forms by the sand travelling first from one side and then from the other.

An instructive example of sand action is represented in fig. 1. Another is to be seen on the pebble-scattered limestone platform on the sea-coast at Nukumaru, New Zealand, where hundreds of sand-worn pebbles are to be seen in every stage of erosion (Plate IV.).

Effects of Changes of Temperature.—This is a powerful agency of denudation in regions where there is a considerable daily range of temperature. In the interior of arid continents there is frequently a range of 40° or 50° Fahr. as between the day and night temperatures. This rapid change of temperature through alternate expansion and contraction introduces enormous stresses in the surface skin of the rocks. The effect of these stresses is to cause the surface of the rocks to peel off in thin irregular flakes. In this way cliffs are slowly disintegrated and the surface of arid plains loosened.

The action is similar to that which takes place when a plate of steel is exposed to the oxidising influence of moist air. A film of rust, that is oxide of iron, forms on the surface. In a short time the alternate expansion and contraction of the plate, due to changes of temperature, cause the rust to peel off in irregular scales. This exposes a fresh surface to the oxidising agent. A new skin of rust forms, soon to be displaced in the same way as the first. Thus, in course of time, the plate becomes corroded and pitted ; and the thinner the plate becomes the more rapidly does the oxidation proceed.

The primary condition of aridity is restricted rainfall, which may be modified by latitude and altitude, topographical barriers, and prevailing winds. In such regions, the ratio of the annual rainfall to the possible evaporation is an important feature.

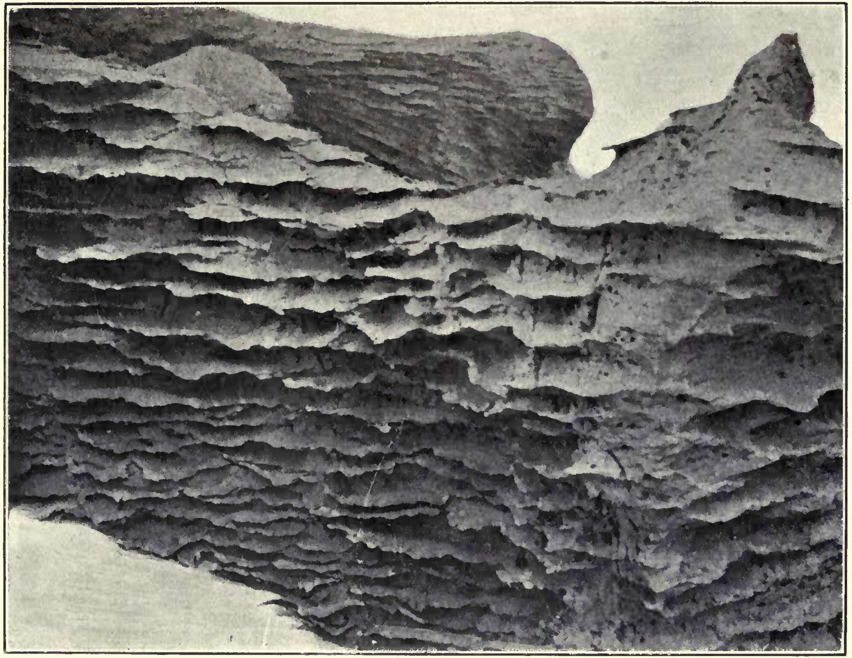
The low relief of arid desert regions and the vast accumulations of loose sandy material that generally abound on them would tend to indicate that *surface-stress* due to changes of temperature must rank among the most active of the processes of disintegration.

THE WORK OF RAIN.

The work of rain is both *chemical* and *mechanical.* By its chemical action it decomposes and softens the surface of rocks, and by its mechanical action it washes away the loosened particles to a lower level. It also decomposes and oxidises rocks as far as it can penetrate.

Chemical Effects of Rain.—Water is sometimes spoken of as the universal solvent. Even when quite pure it can readily dis-

To face p. 20.] [PLATE II.



Photo, L. Cockayne.]

ROCK EROSION BY WIND-BORNE SAND. REEF POINT, NORTH-WEST AUCKLAND.

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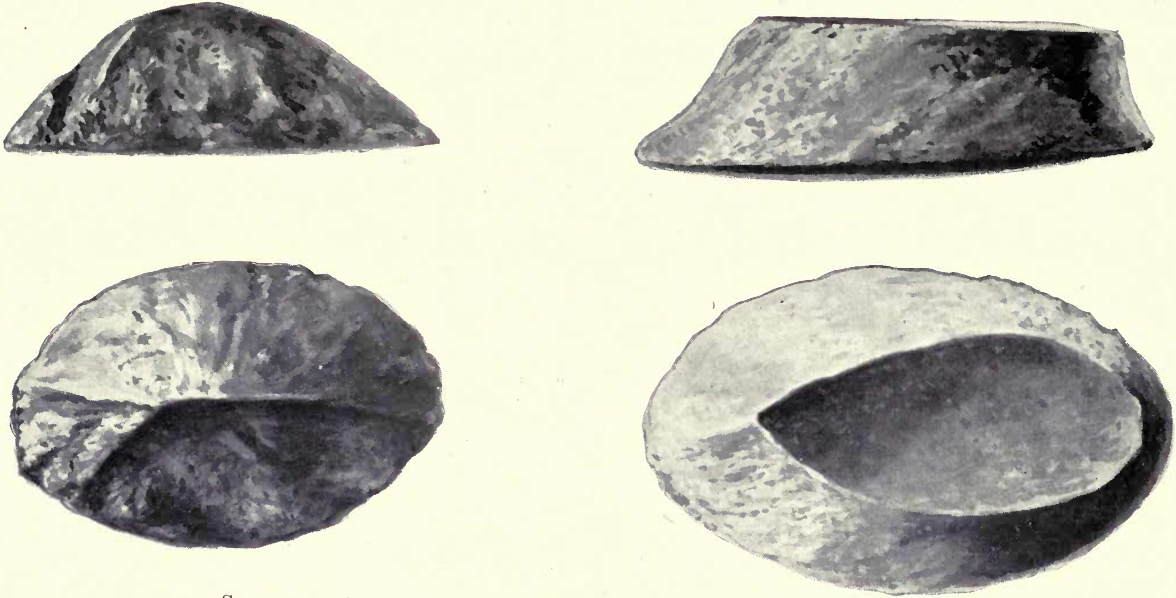
[PLATE IV.



SAND-WORN PEBBLES OF AUGITE-ANDESITE, WAITOTARA, NEW ZEALAND.

solve rock-salt and many sulphate minerals. When it contains dissolved salts or gases its power as a solvent is greatly increased.

The chemical effect of rain-water is only distinguished from that of moist air by its greater activity. Its dissolving and decomposing action, like that of moist air, is mainly dependent on the carbonic acid and oxygen which it gathers from the air as it falls.

Rain acts with greater energy than moist air because it brings to bear on a given place a larger quantity of carbonic acid and oxygen. Besides, by its mechanical effect it washes away the loosened particles, thus exposing fresh surfaces to be acted on by the contained gases. Moreover, the field of action of rain is wider than that of moist air ; for not only does rain act on the surface of the rocks, but it also soaks into the pores and interstices, decomposing and weathering the constituent minerals as far as it can reach. It is in this way that granites, which crop out on moorlands and other low-lying situations where the natural drainage is slow, frequently become decomposed to a depth of many feet. This decomposition, as we have already seen, is the work of the carbonic acid, which attacks the felspar—the silicate of alumina and potash—with great energy. The potash unites with the carbonic acid, forming a carbonate of potash which is soluble in water. With one important constituent broken up, the other constituents are loosened. Outcrops of granite that have been disintegrated in this way can be easily excavated with a pick, and in some cases dug out with a spade.

The milky white clay that is found mixed with the loosened quartz grains and mica scales is the silicate of alumina liberated from the decomposed felspar. It is the mineral which forms the commercially valuable deposits of Kaolin so often found in the vicinity of granite outcrops.

Rain-water is always a carrier of carbonic acid ; hence, when it finds its way into cracks and joints in limestone, the rock is slowly dissolved and in this way the cracks become wider and larger. The caves and underground tunnels and passages that are so prevalent in limestone formations are merely cracks or joints that have been enlarged by the action of surface-water containing carbonic acid.

Rain is also a conveyor of oxygen gas. Hence we find that wherever surface-water has penetrated, the rocks are always more or less oxidised and decomposed. The most obvious effect of this decomposition is the staining of the rock a yellow or rusty-brown colour, due to the oxidising of the iron protoxide and sulphides as previously described. As may be observed in many quarries and railway-cuttings, the oxidised yellow-coloured portion of a rock is always softer and more friable than the underlying unoxidised blue portion.

In the course of mining operations, rocks are sometimes found to be oxidised to a depth of 50 or even 100 feet below the surface. In some of the Kimberley diamond mines in South Africa, the oxidised zone, or what is locally known as the *yellow ground*, descends to a depth of 100 feet. Below the yellow ground comes the unoxidised rock called *blue ground*.

It should here be noted that the oxidation of ferrous oxide in the presence of moisture results in the formation of the hydrous ferric oxide called *limonite*, which, as before stated, imparts its characteristic yellow and rusty-brown colours to rocks within the zone of weathering.

Weathering and oxidation are found to proceed most rapidly along cracks and stratification planes, because it is along these that surface-water can most easily find its way. When the rock is crossed by two systems of joints crossing each other at nearly right angles, in the earlier stages of weathering, the only signs of oxidation are confined to the walls of the cracks. As the weathering proceeds the unoxidised portion gets smaller and smaller until only a core of unaltered rock is left. When the oxidation is complete no unoxidised core of solid rock remains.

Spheroidal Weathering.—A rock-mass that is intersected by two systems of joints lying at right angles to one another is obviously divided into a series of cubes or cuboidal blocks. It is found that when some ferruginous sandstones, claystones, and basalts are jointed in this way, the weathering proceeds in concentric layers around each block, the layers frequently presenting various shades of yellow or brown. When the blocks are exposed on the face of a cliff or cutting, the different layers are found to exfoliate or peel off like the successive coats of an onion. This process of weathering is termed *spheroidal weathering* (Plates V. and VI.). In the case of greywacke, granite, basalt, andesite, phonolite, and most igneous rocks, it is not uncommon to find a core of solid undecomposed rock in the centre of the spheroid.

Effect of Rain on Sulphides.—The oxidising effect of rain-water is very noticeable in the case of sulphide ore-deposits. By long-continued exposure to the action of descending surface-waters, the outcrops of iron, copper, and silver sulphide lodes are frequently oxidised and so altered as to bear little resemblance to the unaltered lode-matter, which is generally found at a greater depth. The iron sulphides are first oxidised to sulphates and then to oxides, while the copper is removed by the water as soluble sulphates, or is oxidised to carbonates which stain the rock green and blue.

The far-reaching effect of rain-water is well seen in the Broken

HORIZONTAL JOINTS AND CONCENTRIC WEATHERING IN GRANITE, MIDDLE GRANITE QUARRY, NEAR WOODSTOCK, MARYLAND. (U.S. Geol. Survey.)

[PLATE VI.

SPHEROIDAL WEATHERING OF ORDOVICIAN CHERT, MISSOURI.
(After Ball and Smith.)

Hill lead and silver mines in New South Wales, and at the celebrated Mount Morgan mine in Queensland, where the ores are oxidised to a depth of over 200 feet below the surface.

Hydration.—Many minerals when exposed to the action of moisture possess the property of absorbing a certain definite proportion of water, a process which is chemically termed *hydration.* Thus, the mineral olivine, when hydrated, becomes serpentine; and anhydride,[1] the anhydrous sulphate of lime, changes into gypsum, the hydrous sulphate, the change being accompanied by an increase of volume amounting to 33 per cent. Hydration is one of the results of weathering, and is confined to the zone of oxidation.

When the hydration is accompanied by increase of bulk the process may cause disruption, fracturing, or disintegration of the adjacent rocks or rock-surfaces.

Mechanical Effects of Rain.—We will now consider the mechanical effects of rain as distinguished from that of running water in the form of streams and rivers.

The principal effect of a pelting rain is to displace the particles of rock loosened by the chemical action of the atmospheric carbonic acid. Under the influence of gravity the particles tend to fall to a lower level where they will accumulate in favourable situations; or perhaps they may find their way into some small trickling stream by which they are slowly rolled downwards until they finally reach a river which carries them towards the sea.

Earth-Pillars.—Another well-known effect of rain is the production of what are termed *earth-pillars.* Miniature examples of these may be seen after heavy rain in many a newly ploughed field, or on the sloping bank of a newly formed road-cutting. A small pebble or flake of stone acts as a protecting cap or umbrella, so that, while the surrounding soil or clay is washed away by the rain, the portions protected by a cap of stone remain for a time forming cone-shaped pillars.

Gigantic *earth-pillars,* in some cases attaining a height of 20 feet or more, are frequently formed in the glacial boulder clays and moraines of Scotland, Switzerland, New Zealand, and other glaciated countries.

Formation of Soil.—The angle of rest of wet clay is 16°; of sand, 22°; and of splintered rock and shingle, 40°. It is therefore obvious that on all surfaces flatter than the angle of rest, the products of weathering and disintegration will tend to accumulate where they were formed, except perhaps on the face of crags and scarps where the rocky face is exposed to driving winds and pelting rain, or the drag of winter snows.

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[1] Gr. *a* = without, and *hudor* = water.

On the loosened weathered crust such lowly forms of plant life as lichens and mosses soon establish themselves, their roots and rootlets penetrating into all the crevices of the disintegrated rock surface. The decaying vegetation produces *humic* and other organic acids which disintegrate the surface still further. Thus, as time goes on, the particles of rock become mixed with decaying vegetable matter, forming a dark-brown vegetable humus or soil.

The thin layer of soil (fig. 2) thus formed soon attracts grasses, shrubs, and trees which, owing to their more vigorous growth, send their roots deeper into the broken crust, and by their decay provide a larger supply of organic matter. In this way the layer of soil becomes deeper and richer, and frequently darker in colour. Moreover, in favourable places, earth-worms carry on their operations, crumbling up and enriching the soil with their castings.

Below the soil there lies the *subsoil*, which consists principally of comminuted rock and clayey material, frequently possessing a yellow or brown colour due to the oxidation and hydration of the iron; and below the subsoil lies the decomposed or partially decomposed rock.

FIG. 2.—Showing graduation from (*c*) rock to (*b*) subsoil, and thence into (*a*) vegetable soil.

The character and fertility of the soil depend on the composition and nature of the rock out of which it has been formed.

Decomposed mica-schist and calcareous sandstones produce *light* soils of great fertility; basalts, limestones, and marls give soils that are commonly *heavy* and fertile; andesites, soils heavy and poor; granite and rhyolite, soils light and poor.

Soils Mechanically Formed.—Besides soils formed *in situ* by the chemical corrosion of the rocks by carbonic and other acids, many soils owe their existence to the mechanical effects of rain and running water. The rain washes the finer particles of rock into hollows and depressions, or carries them within the influence of some stream, by which they are borne seaward. In times of flood when the stream or river overflows its banks, the mud-laden waters deposit a layer of silt over the adjacent lands. According to the duration of the inundation and the amount of matter held in suspension, so is the thickness of the deposit. It is in this way that the rich *alluvial* flats at the estuaries of rivers and in river valleys are formed.

Alluvial flats are to be seen in almost every country ; but perhaps there is no better example of the mechanical formation of soil, or one of more historic interest or economic importance, than that of the Nile, the seasonal inundation of which deposits a fresh layer of silt over the surface of all the alluvial lands bordering the river.

ACTION OF SPRINGS.

Accurate gaugings of the discharge of streams has shown that only a certain proportion of the rainfall within a given watershed is discharged to the sea. The *run-off*, as it is termed, is dependent on the amount of evaporation, the steepness of the contours, the presence of forests, and the character of the rocks within the drainage area. In arid regions the run-off may not amount to more than 10 per cent. of the rainfall, and in only a few cases does it anywhere exceed 40 per cent. This means that a large quantity of the rain-water soaks into the soil and rocks.

Many rocks are so open or porous in texture that they are what is termed *pervious*, and rain-water slowly sinks into them until an *impervious* bed or stratum is reached. When this happens the water flows along the impervious stratum, and if this stratum comes to the surface the water issues as a spring.

Calcareous Waters.—In its slow percolation through the pores of the rocks, the water dissolves certain constituents and thus becomes more or less charged with mineral matter. For example, water that flows through a limestone formation is found to be *hard*, this hardness being due to the dissolved bicarbonate of lime contained in the water.

What is termed the *temporary hardness* of water is represented by the bicarbonate of lime that is precipitated as carbonate of lime, when the water is boiled. The boiling disengages the molecule of CO_2, which enabled the water to dissolve the carbonate of lime, and thus permits the carbonate to be deposited as a solid incrustation in the vessel. The *permanent hardness* of water is the hardness that remains after the carbonate of lime has been precipitated by boiling. It is mostly caused by sulphate of lime, which is not thrown down by boiling.

Waters possessing a high degree of temporary hardness are injurious to steam boilers on account of the hard incrustations they deposit.

Where calcareous waters reach the surface they frequently deposit a white crust of carbonate of lime round the objects over which the water flows. This *calcareous sinter*, or *travertine* as this deposit is called, is generally porous in structure, and often contains the *petrified* remains of mosses, twigs, and various plants that grew within reach of the spring.

Stalactites and Stalagmites.—When rain-water in its underground journey through limestone has widened out a fissure to the dimensions of a cave, the slow drip of calcareous water from the roof allows the feebly attached carbon dioxide to escape once more into the air, and in this way the carbonate of lime is deposited as a thin ring. As drop succeeds drop, the ring of carbonate grows thicker and longer, in time forming a long tube which, by subsequent deposit inside, becomes solid. As the process goes on, so the pendent deposit grows longer until it forms what is termed a *stalactite*, which in form somewhat resembles an icicle of frozen water.

The drops of water fall on the floor of the cave and deposit more carbonate of lime. In this way there is built up a solid pillar or *stalagmite* that in many cases unites with the depending stalactite, forming a continuous pillar reaching from the floor to the roof. Stalactitic calcareous deposits always possess a beautiful radiating fibrous structure.

Caves and underground caverns are common in limestone regions in all parts of the globe. Among the best known are the Mammoth Caves in Kentucky, Wyandotte Caves in Southern Indiana, Peak Caves in Derbyshire, Dachstein in Upper Austria, Jenolan Caves in New South Wales (Plate VII.), and Waitomo Caves in New Zealand. Many streams and rivers flow for miles in underground channels or caverns, the extent of which has not yet been disclosed.

Ferruginous or Chalybeate Springs.—Rain-water in its passage through rocks containing sulphides frequently becomes charged with iron salts. When the water issues at the surface the iron, through the action of the atmospheric carbon dioxide, is converted into the ferrous carbonate. The carbonate is rapidly oxidised by the oxygen of the air into the hydrous oxide which falls as a yellow or foxy brown precipitate. In this way are formed the limonite (hydrous peroxide of iron) veins so frequently found traversing ferruginous sandstones and altered igneous rocks. The variety of the hydrous peroxide known as *bog-iron ore* is formed in the bottom of swamps and lagoons by the same series of reactions, aided by the operations of certain species of bacteria.

Brine Springs.—The underground waters that in the course of their journey come in contact with rock-salt or with rocks impregnated with that mineral become strongly saline, and where

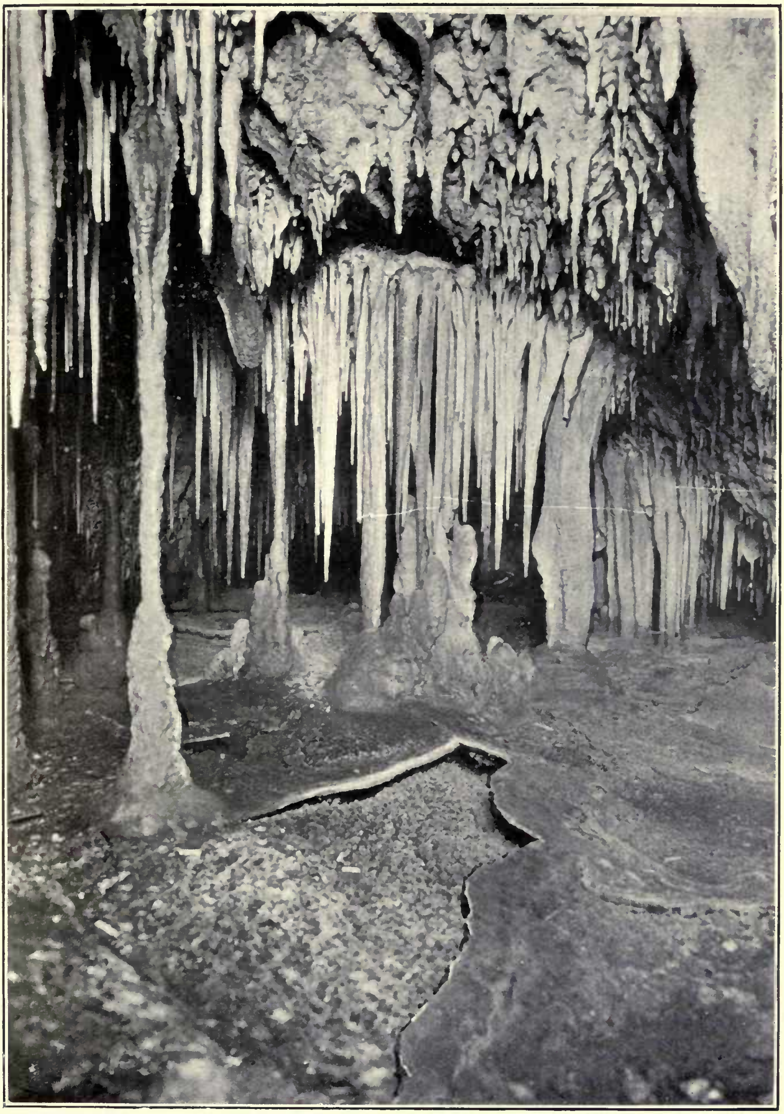

Photo. by O. Trickett.]

MAFEKING GROTTO, JENOLAN CAVES, NEW SOUTH WALES.

they appear as springs, bring large quantities of the dissolved salt to the surface. Brine derived from artificial wells made by boring is a valuable source of salt (chloride of sodium) in Cheshire, in England, and Rex in Switzerland.

Mineral Springs.—These are found both cold and hot. Some are alkaline, containing carbonates of soda and potash, and bicarbonate of lime; others are acid, containing hydrochloric or sulphuric acid mostly combined with lime, magnesia, soda and potash. Free hydrochloric and sulphuric acids are frequently present in large amount in the hot mineral waters that abound in some volcanic regions.

In regions of expiring volcanic activity hot mineralised springs are quite common. Notable examples of these are found in the Yellowstone National Park in the United States, in the North Island of New Zealand, and volcanic regions of Japan.

Geysers and hot springs very frequently deposit silica or *siliceous sinter* around their vents and on the walls of their passages. In this way enormous deposits of sinter have been formed in Iceland, Yellowstone National Park, and Rotorua, New Zealand.

The silica exists in the water in the form of soluble alkaline silicates, and it is deposited on reaching the surface, partly owing to the decrease of temperature and pressure, and partly owing to the atmospheric carbon dioxide uniting with the alkalies whereby the silica is liberated.

Oil Springs.—Petroleum is sometimes brought to the surface by springs and spread as a film over sheets of stagnant water. All the productive oil-wells are, however, made by boring holes to a porous stratum saturated with the mineral oil. Some of the *gushers* in the Texas, Baku, and Maikop oilfields have yielded many thousands of barrels of oil per day.

THE WORK OF FROST.

In countries where the temperature falls below freezing in winter, frost is always an active agent in disintegrating and disrupting rocks. The principle underlying this is the circumstance that water in the act of freezing expands in volume, particularly that which contains dissolved gases. When the expansion takes place in a sealed vessel or bomb, the pressure exerted by this expansion is almost irresistible, amounting to 2000 lbs. per square inch.

Rocks and soils are always porous and contain a good deal of water. When this water freezes, the particles are pushed a little apart. As the result of alternate thawing and freezing, the particles are forced further and further apart until they are finally broken off the parent rock. In this way the surface of porous sandstones and sandy limestones is disintegrated, crumbling away in small flakes.

The destructive effect of frost is strongly marked among the higher mountains where the winters are severe. Water finding its way into the cracks and fissures of the rocks exerts such enormous disrupting force that even large slabs are broken from the solid formation. In many regions the crests of the mountains have thus become covered with a waste of angular slabs broken up by the frosts of many winters.

Mountain slopes are frequently covered with a mantle of loose angular fragments reaching in places from the crest to the base, forming what is known as a *scree, talus*, or *shingle slide.* Where the rock is of a friable character, such as a claystone or slaty shale, easily acted on by frost, the scree may extend along the slope of the range for many miles; but where the rock is of a more resistant character, the scree generally takes the form of a cone which tapers to smaller dimensions as it reaches upward.

The apron of tumbled rock fragments and blocks which accumulates at the base of most cliffs and escarpments is called a *talus*.

SUMMARY.

From what has been said in the foregoing pages we find that the general effect of the different agents of denudation is to waste and degrade the surface and edge of the dry land.

The agents of subaerial denudation range themselves in two main groups, namely: those which operate slowly and almost imperceptibly, but none the less surely; and those that work energetically, but in a narrower field.

The first group includes air, rain, and frost; the second group, streams, rivers, and the sea. In this chapter we have only dealt with the first group, and in a general way we may summarise their work as follows:—

(1) Moist air and rain decompose the surface of rocks by dissolving or breaking up certain constituents, or by removing the cementing matrix.

(2) The principal agent in this process of decomposition is atmospheric carbon dioxide acting in conjunction with water.

(3) The minerals principally acted on by aqueous solutions of carbonic acid are aluminous silicates containing such bases as potash, soda, lime, or iron. These silicates are found in all igneous rocks, and in many sandstones and schistose rocks.

(4) The rocks removed or broken up by the direct dissolving

action of carbonic acid are limestones of all kinds and calcareous sandstones.

(5) The decomposition of a constituent mineral or the removal of the cementing medium permits the rock to crumble up or become disintegrated.

(6) The yellow and rusty-brown colour of soils, clays, and weathered rocks is due to the oxidation of the iron present in the silicates, or to the oxidation of sulphides, or of magnetite, the black magnetic oxide of iron.

The oxygen contents of the three principal oxides of iron are :—

		Ratio.	
		Iron.	Oxygen.
Protoxide	FeO	1	1
Magnetite (Protoperoxide)	Fe_3O_4	1	1·25
Red or brown Hæmatite (Peroxide)	Fe_2O_3	1	1·50

In the presence of moisture the atmospheric oxygen soon converts the protoxide and magnetite into the peroxide. In this way rocks are weathered wherever surface water can find its way.

(7) In the interior of arid or rainless regions, the changes of temperature as between day and night disintegrate the surface of the rocks by alternate expansion and contraction, in the same way as scales of rust are thrown off steel plates and rails.

(8) The wind piles up loose sand into dunes and ridges along the sea-coast, and in continental desert areas.

(9) Caves are formed in limestones owing to the enlarging of fissures by the dissolving action of the carbonic acid carried in solution by rain-water.

(10) Frost causes the breaking up of rocks by the expansive force exerted by water when it freezes.

(11) Underground water when it appears at the surface forms springs. Calcareous waters deposit carbonate of lime in caves, forming stalactites and stalagmites.

(12) Ferruginous waters deposit peroxide of iron where they issue at the surface, and also in swamps and lagoons, forming bog-iron ore.

(13) Geysers and hot mineralised springs are abundant in regions of expiring volcanic activity.

(14) Hot springs containing silica in solution deposit the silica where they issue at the surface, forming layers of siliceous sinter.

CHAPTER IV.

THE WORK OF STREAMS AND RIVERS.

When rain falls a portion soaks into the pores and interstices of the rocks and soil, while the remainder flows over the surface in hesitating trickling streamlets. On their downward course a number of these streamlets unite and form brooklets which, lower down, grow in size and volume until they become large brooks. Finally, the larger brooks unite and form rivers which may discharge their waters into the sea or a lake.

The sea or lake is the lowest level which the river can find, and is hence termed the *base-level.*

The flowing water descends, or falls, under the influence of gravity ; and in its haste to reach its base-level it follows the line of least resistance. Hence in its downward course it bumps heavily against every obstruction that lies in its path. The finer particles it picks up and carries away bodily in a state of suspension. The heavier grains are partly pushed and partly carried along the bottom in a state of semi-suspension ; while the pebbles and boulders too heavy to be lifted are rolled onward, one over another. Against the rocks that are too heavy to be moved the water frets and chafes continually until at last the obstruction is removed, the removal being effected mainly by mechanical erosion, but also partly by chemical dissolution of the rock, or of some of its constituents. The erosion of the land and the transport of material are happenings merely incidental to the passage of rain-water to the sea.

GEOLOGICAL WORK OF STREAMS AND RIVERS.

Running water in its journey to the sea performs a double *rôle.* It acts both as an agent of *erosion* and *transport.*

Erosive Work of Streams.—The erosive work of streams is partly *chemical* and partly *mechanical.*

The waters of all streams contain dissolved carbonic acid and oxygen which act slowly on all the rock surfaces with which they come in contact. The rate of dissolution of the rocks is imperceptible and too small to measure, except in the case of limestones and calcareous sandstones, which, in river courses, are frequently worn into wide cavities or underground channels.

Chemical analyses have shown that all river-waters contain a certain proportion of dissolved mineral matter generally varying from 10 to 40 parts in 100,000. Of this dissolved matter bicarbonate of lime constitutes the major part.

Water is an almost perfect lubricant; hence its erosive or abrasive action, mechanically considered, is practically *nil*. But when running water transports particles, grains, or pebbles of solid matter, it becomes a powerful agent of erosion; its work being strikingly seen in many deep water-courses and profound gorges.

The excavating and erosive power of rivers depends on (1) the rate of flow; (2) the character of the transported detritus; and (3) the character and arrangement of the rocks through which the channel is excavated.

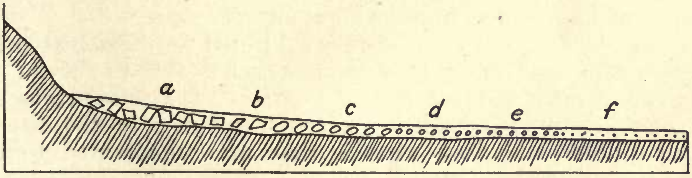

FIG. 3.—Showing graduation of river-drift.

(*a*) Zone of angular blocks.
(*b*) ,, semi-angular blocks.
(*c*) ,, rounded boulders.
(*d*) Zone of well-rounded gravels.
(*e*) ,, water-worn sands.
(*f*) ,, silt and mud.

The Influence of Rapid Flow.—When the flow is rapid the excavating power is relatively greater than when the flow is slow; for not only do the travelling sands, pebbles, etc., abrade with greater force, but a larger quantity of them is brought into action against a given place in a specified time. The pebbles and loose stones that are rolled onward along the bottom rub one another as well as the rocky channel, until they are reduced to the condition of fine sand or mud. By this rubbing and grinding action the sides and bottom of the river-bed are widened and deepened. Pebbles and boulders that have been rolled along the bottom of a river are always smooth and generally possess a rounded or roughly oval shape.

The rocky material in a river that traverses a broken mountainous country is commonly rough and angular near the source (fig. 3), but it becomes smoother, rounder, and smaller in size the further it is transported. In the upper part of the valley the channel is frequently piled up with large angular slabs and masses of rock that have fallen down from the heights above where they have been broken off by the action of frost or rain. The waters plunge below, around, and over the obstructing masses against which they wage an unceasing war. Lower down the valley the angular blocks give place to semi-angular blocks of smaller dimensions. Still lower down, only rounded boulders are seen; and in the lower reaches these are progressively succeeded by gravels, sand, and mud.

Rivers of great length that traverse wide stretches of flat land in their lower course, such as the Mississippi in North America, the Amazon in South America, or the Yang-tse-kiang in China, transport only fine sand and silt to the sea. On the other hand, rivers with short courses and steep gradients, such as those draining the Southern Alps of New Zealand, discharge enormous quantities of coarse sand and gravel into the adjacent open seas.

The rocky debris in a river-bed is subjected to so much attrition and grinding that only the harder material is able to survive for any considerable distance from the source. The softer rocks are soon broken up into small fragments or reduced to the size of small pebbles, and these after a time are comminuted to the condition of mud or silt.

If we examine the rocky material in the bed of a stream rising in a region composed of granite, mica-schist, slate, and limestone, we shall find that near the source angular masses of all these rocks will be piled up in the channel. As we proceed lower down the stream, the proportion of granite boulders will gradually increase until in a few miles they greatly predominate. Still further down, schist, slate, and limestone pebbles and slabs will become fewer and fewer until granite only is represented in the river-gravels, together with quartz, pebbles, and sand derived from the broken-up mica-schist or from fragments of disintegrated granite.

Thus we find that while an examination of the gravels in the lower reaches of a stream will give us evidence of the existence of certain rocks within the drainage area of the stream, it may utterly fail to give a complete view of all the rocks actually present within the watershed. There may exist at the source or in the upper reaches chalk or other soft limestone, shales, or even a whole series of Tertiary formations, none of which may be represented in the detritus in the lower reaches.

The presence of blocks or boulders of a certain rock among the gravels of a river cannot be always taken as conclusive evidence that the rock exists *in situ*, *i.e.* in place, within the drainage area of the river in question. It is not infrequently found that in regions at one time covered with glaciers, blocks of stone have been transported from one watershed to the other, and thus find a resting-place among rocks to which they are strangers. Such ice-borne blocks, or *erratics* as they are termed, are not uncommon in the glaciated portions of Great Britain, Northern Europe, New Zealand, and elsewhere.

The Erosive Effects of Floods.—All streams and rivers are subject to seasonal or periodic floods. These floods may be due to the melting of snow on the higher ranges during spring and summer, or to abnormal rainfall at any time of the year. By thus increasing the volume and depth of flow the transporting and eroding power of the current is enormously increased.

The velocity of a river, on the same slope and with the same cross-section, varies as the cube root of its volume; and its transporting power varies as the sixth power of the velocity. That is to say, if the volume of a stream is increased eight times, its velocity will be doubled as $\sqrt[3]{8}=2$; and its carrying power be increased sixty-four times as $2^6=64$.

The influence which changes of velocity exercise on the transporting power of a stream or river is almost incredible, but will be in some measure realised from the following statement:—

Velocity.	Carrying power.
1	1
2	64
3	729
4	4096
5	15625

Let us take an actual case. The normal flow of the Shotover River in New Zealand amounts to 350 cubic feet per second, but the flood volume is about 9500 cubic feet per second, equal to an increase of twenty-seven times. Hence the normal velocity is trebled, as $\sqrt[3]{27}=3$. In other words, the transporting power of the river is increased over seven hundred times; and during flood-times it can carry masses of rock weighing a ton as easily as 3-lb. pebbles when the flow is normal.

Blocks and boulders that a stream could not even move at times of normal flow may be carried down the channel for many miles, there to be left stranded as obstructions in the channel until a greater flood moves them still further down.

During floods the banks are rapidly undermined and crumble away, and in this way the river-bed is widened or new channels formed.

In 1842, a vast landslide, caused by a flood, blocked the Indus below Bunji, submerging the valleys for a length of 36 miles. In

1896, a glacier blocked the Suru Valley in the Himalayas, and the imprisoned water when it burst through devastated the country below for 40 miles.

In country possessing steep slopes the rain soaks into the ground, and, accumulating on a clayey face or impervious rock, causes landslips or landslides to take place. The tumbled rocky debris forming the slide may reach down to the river torrent, by which it is soon swept away; or it may fall bodily across the river-channel, damming back the water for a time. When the pent-up flood at last breaks away it carries everything before it. Even small brooks that normally are incapable of moving anything larger than a grain of sand, in times of flood may become raging torrents capable of displacing millions of tons of rocky debris in the course of a few hours.

The bed of many streams and rivers is covered with a protecting screen of gravel, sand, or mud of varying depth. That is, it may be only a few inches deep, or as much as 50 feet in the case of large rivers.

At times of normal flow this protecting cover is almost stationary, but during floods it is rolled down stream, its place being taken by fresh material transported from the higher reaches.

The majority of streams and rivers, for at least a portion of their course, flow over a rocky bed, free or nearly free from travelling gravel. When this happens the floor of the channel frequently exhibits many inequalities, and this is particularly the case where the stream flows over rocks of different degrees of hardness and toughness, the softer rocks being worn into depressions, while the harder form bars and obstructing reefs.

Formation of Pot-Holes.—A striking, but not uncommon, feature of many rocky river-beds is the presence of *pot-holes* of various shapes and dimensions. These holes, which are generally round and cauldron-like in form, are more common where the bed is steep than elsewhere. They are formed by the rocking and grinding action of a hard boulder moved by the swirling eddies and acting for a long time at one point. When the pot-hole has become large enough, it is liable to be invaded by one or more new boulders which by their united action may enlarge the hole until it is many feet deep and many yards wide.

Erosive Effects of Transported Material.—The sands, gravels, and boulders carried onward by the current of a stream, besides acting on one another, also grind away the floor and sides of the channel, which is thereby gradually deepened and widened. In other words, their erosive[1] effect is both *vertical* and *lateral*, and

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[1] *Corrasion* is a variant of corrosion that has been used by some writers to denote the vertical excavation performed by a stream. The term does not seem preferable to the word erosion commonly used by English geologists.

the harder and tougher they are, the greater will be their abrasive power. The erosive effect of fine matter held in suspension is very feeble, the greatest amount of excavation being effected by the semi-suspended sands, and by the gravels that are rolled and pushed along the floor.

Erosion of Different Rocks.—The excavation of soft rocks is more easily accomplished than that of hard rocks; for this reason a stream will frequently bend from its normal direction to follow along the course of a soft and easily eroded formation. In places where a river is compelled to cut through a stretch of hard rocks its channel is generally deep and narrow, the flowing water in seeking its base-level showing the same economy in excavation as the miner in cutting his water-race through the same class of ground.

Where the rock-formation is soft and comparatively easy to excavate, the channel is nearly always relatively wide and shallow.

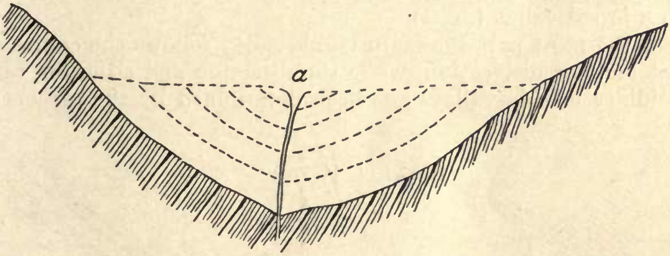

Fig. 4.—(*a*) Joint forming initial water-course and afterwards widened into a broad valley. The dotted lines show the progressive widening of the valley.

Factors in Selection of River-Course.—The causes which have led to the selection of the course followed by rivers in their descent to the sea are various. In the main they may all be said to result from the natural tendency of the water to find its base-level by the shortest and easiest route, for brook and river alike will select the route that offers the least resistance to their downward course.

If left to itself, a stream will always excavate its course in a soft formation in preference to a hard one; and follow a line or zone of shattered rock rather than cut a channel through a compact unbroken formation. In every case water will follow an opening or crack already formed rather than cut a new channel for itself.

Observations in the field in many lands have shown that the main valleys of many rivers follow the course of powerful faults or crustal dislocations; or follow lines of subsidence resulting from the operation of a system of parallel faults; or run in depressions left by the uplift of parallel mountain blocks.

As we shall later find, many rocks are traversed by one and sometimes two series of more or less parallel cracks, known as *joints*. Water finds its way along these quite easily. In process of time the joints become enlarged by erosion into water-courses, and in this way we have the beginning of what may afterwards open up into a broad valley (fig. 4).

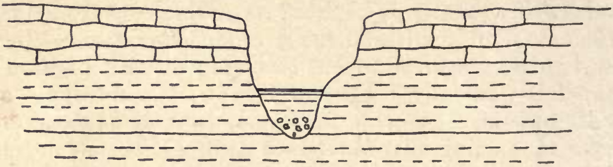

FIG. 5.—Gorge in plateau.

For the most part the main trunk valley follows the course of a great fault or dislocation, while the direction and situation of the subsidiary or side valleys has been determined by the presence of smaller lateral faults, joint planes, or the existence of zones of soft rock.

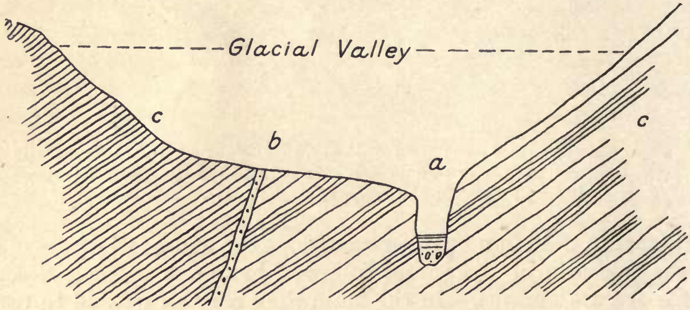

FIG. 6.—Profile of Shotover Valley, N.Z.
(*a*) Shotover R. (*b*) Shotover Fault (*c*) Mica-schist.

Gorges.—Where water flows through a rift in compact rock, and the gradient is steep, it soon, geologically speaking, excavates for itself a narrow rocky channel. Where the channel is deep, with steep sides, it is termed a *gorge*.

The gorge may be excavated through a plateau or tableland (fig. 5), or in the floor of a broad ancient glacial valley; or it may cut through a mountain-chain.

In recently glaciated countries there are to be found many fine examples of gorges excavated along the floor of ancient glacial valleys (fig. 6).

Cañons.—Cañons are profound river-gorges with steep walls. They are a feature of deeply dissected plateaux where the uplift and consequent river erosion have been rapid. Their depth is always great in proportion to their width.

The most remarkable known example is the Grand Cañon of Colorado, which extends from the flanks of the Rocky Mountains to the head of the Gulf of California. The river has cut its channel for 500 miles across the desert plateau, which consists of practically horizontal sedimentary strata of various ages, Palæozoic, younger Mesozoic, and earlier Cainozoic, piled on a floor of ancient granite.

The grandest and most picturesque part of the cañon is chiefly cut through Carboniferous and Permian strata. The maximum depth is 6000 feet below the surface of the plateaux. (See frontispiece.)

Two phases of development may be traced when the cañon is viewed in cross-section, namely, an upper normal valley with a flat floor, and the cañon proper cut in the floor of the upper valley. The upper valley is many miles wide and bounded by alternating steep wall and moderate slope, their edges in many places notched with short ravines. The inner cañon is a narrow trench, bounded by deeper and steeper walls that are in places 3000 feet high. It was cut by the river owing to an acceleration in the rate of uplift after the excavation of the upper valley.

The Grand Cañon is a stupendous example of river erosion, and has no parallel in any part of the globe. Notwithstanding its vast depth, the steepness of the walls is an evidence that it is the work of a river still in the youthful phase of its existence.

The Highlands of New South Wales, comprising the uplands of New England, the Blue Mountains, and the Darling Downs, owe their existence to the dissection of an ancient plateau by rivers which have cut deep valleys and cañons, the latter with steep walls 600 feet in height.

Waterfalls.—Where a stream or river has cut its channel in a rock-formation consisting of alternating layers of varying hardness, it frequently happens that a waterfall is formed. The softer rock is eroded at a greater rate than the harder, with the result that the stream-bed is excavated into platforms at different levels. Where the descent from one platform to another is vertical a waterfall is formed, the water falling bodily from one level to the other (fig. 7); and where the descent is steep but not vertical, there is frequently a number of small waterfalls or *cascades*. In places where the slope is comparatively low, the rapidly flowing current is broken up into what is termed a *cataract* or *rapid.*

Recession of Waterfalls.—Where the strata are lying horizontal, or nearly so, and the cornice over which the water tumbles is much harder than the underlying beds, the waterfall slowly recedes upstream. This recession is due to the undercutting of the cornice, which gradually crumbles away under the weight of the flowing water. In this way the gorge or ravine of the river is lengthened.

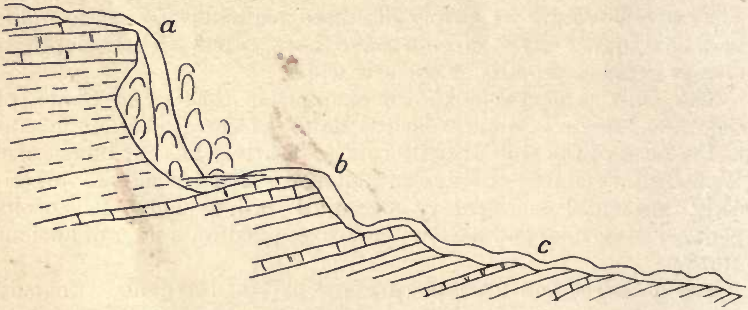

FIG. 7.—Profile of waterfall.
(*a*) Waterfall. (*b*) Cascade. (*c*) Rapids.

FIG. 8.—Falls of Niagara.

One of the most striking examples of recession is that afforded by the Niagara Falls (fig. 8), which have receded a distance of seven miles in late geological times, the rate of erosion amounting to about 4½ feet a year.

Although recession is most marked in the case of horizontal strata capped with a hard cornice, it is certain that it takes place in all waterfalls independently of the inclination of the strata. Moreover, in some volcanic regions many fine examples of retreating waterfalls (fig. 9) are seen in places where rivers flow across streams of lava that alternate with beds of loose or only partially consolidated ash.

The Winding of Streams and Rivers.—The tendency of a rapid stream is to flow in a straight course, and in order to attain this end it will act with great energy on any obstructions that lie in its path until they have been removed. When the stream emerges from the highlands, where its gradient is steep, and passes on to flat or undulating ground, where its rate of flow is slow and its excavating power therefore relatively feeble, it is generally found to pursue a tortuous course frequently meandering about the plain in a series of bends and loops that sometimes overlap or almost touch each other.

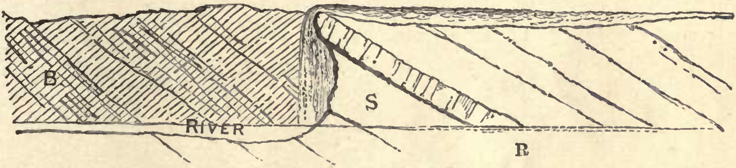

FIG. 9.—Section of river gorge, showing progress of recession.

The stream, having only a sluggish flow and little eroding force, avoids every obstruction it meets, whether it is a hard band of gravel or a boulder ; and in this way it bends first one way and then the other.

At all times the main current is directed against the concave bank, from which it is deflected to the opposite bank. The greatest erosion, therefore, takes places on the concave bank, which during times of abnormal flood is frequently undermined and thus crumbles away. In course of time the bend becomes sharper and larger, until in many cases the area of land between two loops is completely removed. In this way comparatively insignificant streams are frequently found to have excavated for themselves channels of great width. The process of excavation will be readily understood by a reference to the next figure.

The current is directed against the bank as indicated by the arrows (fig. 10), so that in course of time the space enclosed within the stream and the dotted lines is worn away. When this has taken place the bends are seen to be sharper. As time goes on the whole of the spaces marked A (fig. 10) lying between the loops are removed, thus forming a wide river-bed. That is, the bends gradually widen and travel downstream until the ground separating them is eventually cut away.

The velocity of the current is greatest against the concave bank and least on the convex side *a*. As a result of this the current drops a portion of its load on the convex side at *a*, where it accumulates and forms a sand or shingle bank.

The General Effect of Denudation.—The total effect of all the subaerial processes of denudation is to lower or degrade the general level of the dry land. It is obvious that if denudation continued long enough, the land would be reduced to a plain not rising much above sea-level.

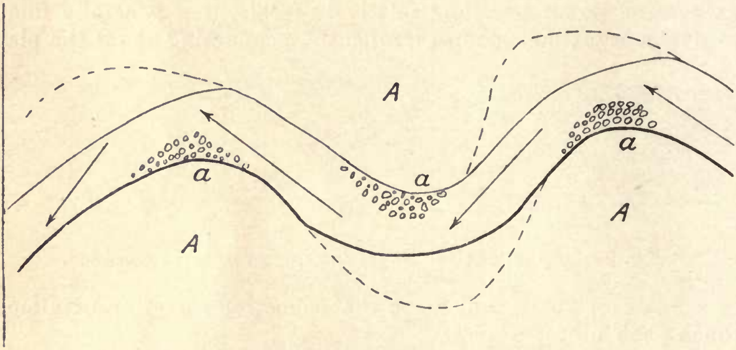

FIG. 10.—Showing winding course of stream.

We have already seen that rivers are fed with detrital matter at their sources, a large proportion of which in a finely divided form is transported to the sea. But a river possesses main tributaries, and the tributaries have their branches. These branches are in their turn fed by streamlets composed of innumerable trickling rills. A river system with its numerous primary, secondary, and tertiary branches covers the land with a network of water-courses, each of which carries its quota of denuded material into the trunk river, whence it is carried to the sea.

It is therefore obvious that in all regions drained by rivers every portion of the surface is continually under the influence of the ever active agents of denudation, and must, therefore, in process of time, be reduced or degraded in level.

The rate of denudation will be greatest in the highlands, less in the foothills, and least in the downs and plains bordering the sea.

It is greatest in the highlands because frosts are harder and the rainfall more copious than in the lowlands. The slopes also being steeper, the broken and disintegrated rocks receive more assistance from gravity in their downward course. Moreover, the gradient of the stream-beds is steeper and the transporting power of the current proportionately greater than in the low country. The degradation of the highlands may be regarded as a species of active warfare in which the rocks are shattered, broken, and ground into gravel, sand, and silt; that of the lowlands as a silent wasting of the whole surface by the slow and almost imperceptible removal of the soil by rain, partly in solution, but mainly in the form of mud or silt.

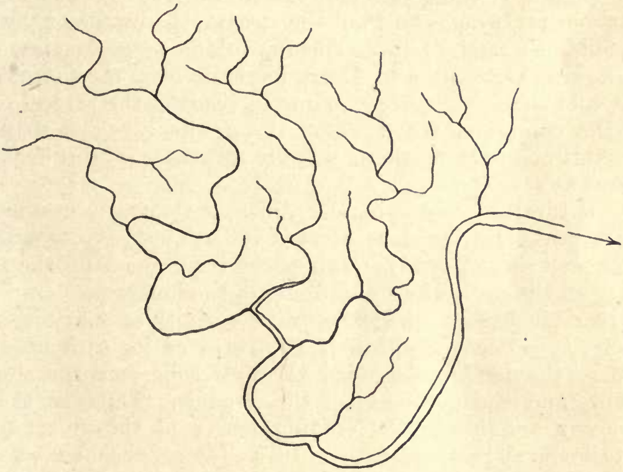

FIG. 11.—Taieri River, N.Z., with its network of tributaries on the north side.

While discussing the effects of the denudation accomplished by running water, it is as well to bear in mind that the elementary function of rain is not to disintegrate and denude the land, but to find its way back to the ocean from which it came. The breaking up and eroding of the land over which the water flows are merely happenings incidental to the haste with which the return journey is made to the parent source.

Development of River Erosion.—When a stream commences the dissection and denudation of, let us say, a plain of deposition gradually rising from the sea, it starts life, so to speak, as a tiny rivulet. As time goes on this infant stream extends its operations. It grows longer, and by draining a larger area gets larger and stronger. With increasing age it is joined by lateral streams or tributaries which, like the parent stream, also extend their courses, and in time are supplemented by the development of branches that also possess other branches in the form of rills and trickling streamlets.

Where the slopes are steep, erosion will occur ; and near the sea, where the gradients are gentle, deposition of the water-borne sediments will take place, so that eventually the whole course of the stream will be reduced to a uniform gradient. When this condition is reached the stream is said to have found its *grade-level.* If the volume of the water and the rate of erosion were uniform throughout the whole course of the stream, the profile of the river-bed would be a straight line. But the volume of all streams, except those flowing across an arid desert, increases from the source downwards, and there is a corresponding increase in the rate of erosion until the point is reached where the gradient begins to flatten. Below this point the erosion gradually decreases until it eventually vanishes at sea-level.

The natural tendency of the differential stream erosion and sedimentation is to produce what is called a *curve of erosion* with the concave side upwards. This curve is obtained by the stream planing off the projections and filling in the hollows.

A river reaches its greatest erosive activity at maturity. But its activity possesses within it the germ of its own decay, for the more the land is degraded the flatter become the slopes of the hills and the gradients of the streams. Thus, as the land gets lower and lower, the eroding power of the river and its tributaries gets less and less, until a stage is reached when the river becomes a mere transporting agent of mud and silt. At last even this action ceases and the cycle of fluviatile erosion is complete. The decadence arising from extreme old age can only be arrested by an increased supply of water, or by an uplift of the land which will once more provide gradients that will again revive the erosive power of the running water.

If the uplift of the land begins at a late stage in the cycle of erosion, say at the time when the river is approaching the exhaustion of its denuding power owing to the land having been worn down to a nearly level plain, a second cycle of erosion will begin on the old plain ; and if no change of conditions takes place, the first-formed plain will be dissected and denuded into a second and lower *plain of denudation.*

Effects of Uplift and Subsidence.—It is obvious that the progressive growth and decay of river-erosion, ending in the formation of a plain of denudation, can only take place if the land remains throughout in a state of rest, neither rising nor subsiding.

The effect of uplift occurring at any time before maturity has been reached will be to increase the erosive activity of the river, while occurring after maturity it will cause rejuvenation.

On the other hand, a subsidence of the land by lowering the gradients will accelerate the decadence of the drainage system, and if continued it will finally lead to extinction by destroying the erosive and transporting power of the river and its affluents.

Development of a River System.—The primary requirement in the development of a river system is progressive continental uplift. Moreover, the nature of the uplift is of material consequence in determining the topographical effects that may be produced by subaerial erosion acting on the surface of the rising land.

When the uplift is uniform, the ultimate effect may be the formation of a deeply dissected plateau of the Colorado type ; but if the uplift is differential, the upward movement being faster along the axial divide of the ancient land than it is along the sea-coast, the result will be the development of foothills characterised by long dip-slopes and corresponding escarpments, the long slopes being presented to the sea.

If the rate of uplift is slower than the normal rate of the marine erosion, the uprising sea-floor with its sheet of sediments will be worn down to a gently sloping plain of marine erosion that will never rise above sea-level ; but if it is faster and continuous over a long period, there will be developed a system of topographical features the form of which will be mainly dependent on the nature of the uplift, the character and inclination of the newly uplifted strata, and the climatic conditions.

Let us consider the case of a uniform uplift in an arid region. If this region is backed by a prominent chain of mountains possessing a copious rainfall, there will be formed an arid plateau composed of horizontal strata deeply dissected by the rivers draining the neighbouring highlands. By such uniform uplift we may obtain a replica of the Colorado plateau with its profound cañons excavated by the rivers that drain the western slopes of the Rocky Mountains.

The same uniform uplift in a temperate region where the annual rainfall exceeds 35 or 40 inches will produce a maritime plain or plateau traversed by trunk rivers draining the ancient highlands, and scored by innumerable tributary streams, by which the surface is carved into a maze of narrow ridges and flat-topped hills. Of such origin is the Wanganui maritime plain in New Zealand, the surface of which is sculptured into a terrain of undulating hills and flat-topped ridges, the survivals of the original plain. In a distance of fifty miles, the younger Tertiary strata, which compose this plain, rise gently from sea-level to a height of 2000 feet as a consequence of the crustal arching of the central volcanic region, the southern limits of which are dominated by Mount Ruapehu, a gigantic volcano girdled on three sides by a ring of limestone escarpment.

Relatively rapid uplift in a moist, temperate latitude accompanied by axial arching, whereby the strata are tilted at angles above 10° or 15°, produces a series of more or less parallel foothill ridges characterised, as already indicated, by long dip-slopes and corresponding escarpments, which are especially well-developed where the uplifted rocks consist of alternating bands of hard and soft material. Many fine examples of this type of topographical feature are found in the maritime regions of most continents where uplift has taken place in late Tertiary times.

The succession of long dip-slopes and steep escarpments that lie between the sea and the Ruahine Chain, in the province of Hawkes Bay, New Zealand, is a beautiful and picturesque example of the work performed by running water during the development of a river system resulting from differential uplift.

The Actual Development.—As a starting-point let us assume an old land-surface forming highlands, and drained by a river running into the sea approximately at right angles to the general trend of the coast-line as shown in A, fig. 11A.

In the second phase, as the result of differential uplift, the sea-floor with its pile of sediments gradually rises until it forms a strip of new land running parallel with the old strand. The ancient river, that existed before the uplift began, still finds its way to the sea ; for, as the uplift progressed, it encountered little difficulty in cutting its channel across the slowly rising truncated edges of the sediments.

The course of the river is transverse to the strike of the uprising beds as shown in B, fig. 11A, and hence is called a *transverse* river.

As the uplift progresses, the transverse river increases in length, and its channel becomes deeper and deeper.

The newly raised maritime strip of land, as shown in the second phase, now forms the foothills of the ancient highlands. The rainfall on the foothills creates small lateral tributaries that run more or less parallel with the strike, their course following the zones of softer rock. And because these streams run approximately along the strike of the uplifted strata they have been called *longitudinal* streams.

So long as the uplift continues, the transverse river and its longitudinal tributaries become longer, and their channels deeper and broader. (C, fig. 11A.)

Where the transverse river cuts through bands of limestone, conglomerate, or other hard rock, the profile of its channel is more or less **V**-shaped. In the softer zones the valley is usually broad and bounded by gentle slopes. Thus, when we trace such a river from its source to the sea, we find that it passes alternately through a succession of deep gorges and open valleys. As a good example we have the great snow-fed Clutha River in New Zealand, which rushes through the picturesque Kawarau Gorge to the Cromwell Basin, then through the profound Dunstan Gorge to the Manuherikia Basin, and finally through the narrow Roxburgh Gorge to the Roxburgh Flats.

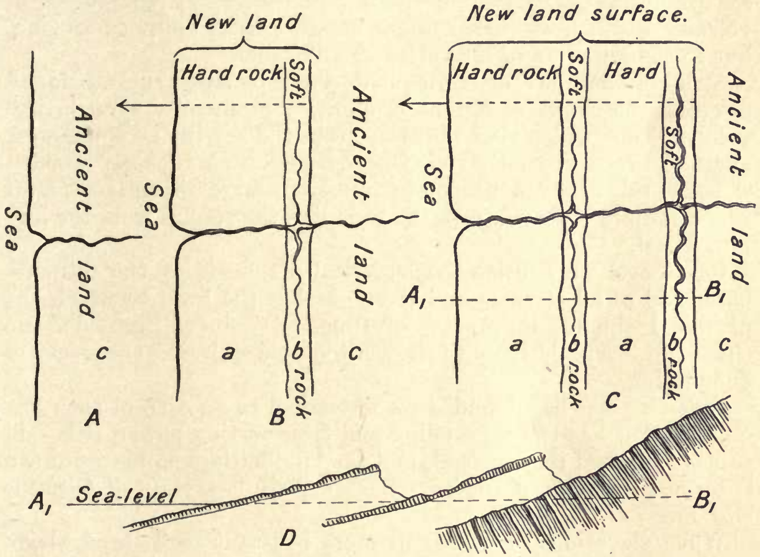

FIG. 11A.—Section on line A_1–B_1, showing development of river system arising from differential uplift.

(*a*) Hard stratum. (*b*) Soft stratum. (*c*) Ancient rock.
(A) First phase. (B) Second phase. (C) Third phase.
(D) Section along line A_1–B_1.

The type of river system which comprises a main transverse river with numerous longitudinal tributaries is most often met with in maritime regions occupied by Cainozoic or younger Mesozoic formations that were laid down marginal to the ancient strands.

Where a plain of marine sedimentation emerges from the sea as an anticlinal ridge or dome, a number of more or less parallel transverse rivers will be developed on each side of the axis of elevation. This structure is well seen in the North of England, where the eastern slopes of the Pennine Chain are drained by a number of large rivers that rise in the central divide. On the west side of the chain the symmetry has been almost obliterated by the uplift of the Lake District and the greater steepness of the Pennine Chain itself.

In the terminology adopted by some geographers, the *transverse* rivers are called *consequent*, because they are the result of uplift; and the *longitudinal* streams, *subsequent*, since their formation is always subsequent to that of the consequent rivers. It is almost a truism to say that all trunk rivers are a consequence of uplift, and hence *consequent*, and the tributaries *subsequent*. The notable exceptions are the streams and rivers that drain the slopes of volcanoes, which owe their origin not to crustal uplift or arching, but to the piling up of lava streams and ashes.

Striking examples of consequent rivers of this type are found draining the slopes of Mount Egmont, a beautifully symmetrical volcanic cone which rises abruptly from the sea in the south-west angle of the North Island of New Zealand. The densely wooded slopes of this cone are drained by numerous large torrential streams which radiate outward from the cone like the spokes from the hub of a wheel.

Base-Level of Erosion.—Theoretically the sea is the ultimate base-level of all streams and rivers, and is the level to which the dry land should, in process of time, be reduced, provided no change of level relatively to the sea took place during the cycle of denudation.

When a river has denuded its watershed to an area of such low relief that it has lost its eroding and transporting power, it is said to have reached its *base-level*, and the land surface so planed down is termed its *plain of erosion*. Such a plain is a *plain of fluviatile erosion*.

When elevations of harder or more resistant rock stand above the general level of the surface, such a plain of erosion is termed a *peneplain*.

Many ancient peneplains have been elevated by faulting, or by slow crustal movement, until they have attained such a height above the sea as to form plateaux.

Peneplain of Arid Erosion.—By long-continued exposure to the disintegrating action of rain, frost, wind, and changes of temperature, the arid interior of continental areas has in some regions become worn down to a nearly level surface, or a level surface dotted here and there with hummocks and elevations of hard rock that have been able to resist the attacks of subaerial denudation longer than the surrounding country. Peneplains of arid erosion frequently occur at a considerable elevation above the sea. Among familiar examples we have the *veldt* or plateaux lands of the Transvaal and the great interior plateau of Australia, on a portion of which is situated the goldfields of Yilgarn and Kalgoorlie.

River-Piracy.—Streams have not always held the course in which they now flow. If a stream cuts back its course and deepens its bed more rapidly than a stream in a neighbouring basin, it may work its way across the intervening divide and rob the head waters of that stream, always provided its bed is deeper than the floor of the valley that has been invaded.

If the valley occupied by stream *a b c* (fig. 12) is deepened more rapidly than the valley drained by stream *g f d e*, a tributary of the former *b c* may cut its course back to *d*, and thereby steal the headwaters *d e* of stream *g f d e*, which is then said to be *beheaded*. The invading stream is known as a *pirate*.

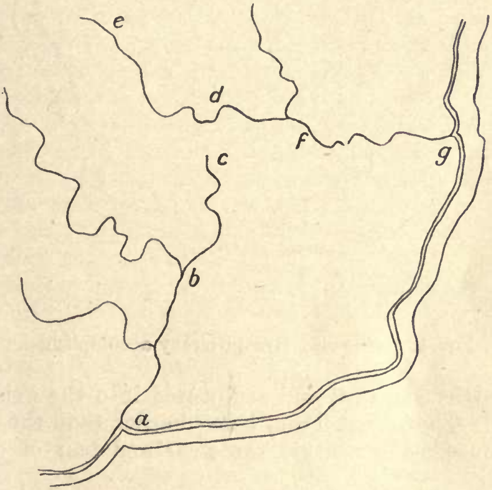

Fig. 12.—Showing progress of stream-piracy.

The beheaded stream is diminished in volume by the amount of water contributed by *d e*, while the volume of the pirate stream is correspondingly increased.

Stream *a b c* with its larger volume of flow now acquires a greater erosive power, and continues to deepen its channel faster than the beheaded stream *f g*. The result of this is that the divide at the head of *f g* is slowly shifted down the valley towards *f*, so that the drainage of the portion of the valley lying between *d* and *f* is in time reversed, as shown in fig. 13.

Protecting Effect of Basalt Flow.—In late Tertiary, that is in quite recent geological time, many of the valleys of the State of Victoria in Australia were invaded by floods of basaltic lava that filled up the river-courses and in places even overflowed the valley walls.

Since the emission of the basalts, the country has been dissected and denuded by streams, and sculptured into the existing ridges and valleys. The basalt-flows, being harder than the older slates and sandstones, have resisted the wear and tear of denudation, with the result that the old valley walls have been worn down into new valleys, while the basalts remain as flat-topped ridges as shown in fig. 14.

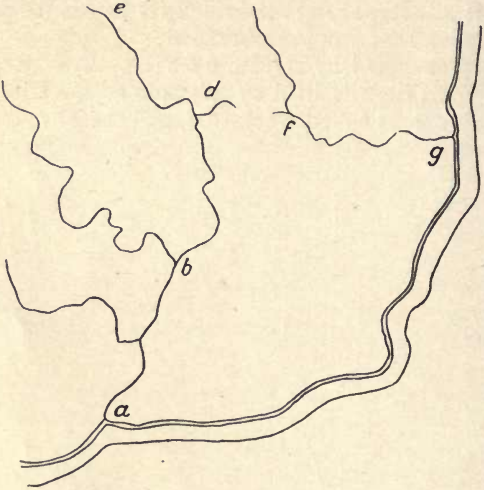

FIG. 13.—Showing stream-piracy accomplished.

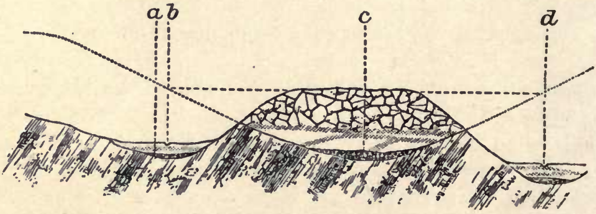

FIG. 14.—Section of Mount Greenock, showing protective effects of basalt-cap. (After A. Brough Smyth.)

(*a*) Wash-dirt in new river-course. (*b*) and (*d*) Existing water-courses.
(*c*) Wash-dirt underlying basalt and marking site of ancient river.

Rate of Denudation.—This relates to the lowering of the whole surface of the land as effected by the united action of all the agents of denudation. The data required for the computation are (*a*) the mean annual rainfall as determined by observations extending over a number of years; (*b*) the area of the watershed; (*c*) the annual discharge; and (*d*) the quantity of suspended matter carried to the sea as found by numerous experimental tests.

The margin of possible error that may be introduced into computations of this kind is always very great, mainly on account of the difficulty and expense involved in the obtaining of trustworthy mean values for the rainfall, run-off, and quantity of transported matter. Even with the best data obtainable the results cannot be regarded as other than wide approximations. When the computation is based on a few isolated observations, the results are likely to be quite misleading and altogether erroneous.

The rate of degradation of two adjacent watersheds enjoying the same rainfall may be quite different. Thus, in the area occupied by the hardest and most resistant rocks the rate will be slowest. Moreover, the mean altitude above the sea, steepness of contour, and climate must be included among the many conditions that may tend to modify the waste of the land.

The Mississippi has been estimated to lower its basin 1 foot in 5400 years, and the Danube 1 foot in 3500 years; while the whole area of England is reduced by subaerial mechanical denudation 1 foot in about 3000 years.

All streams and rivers carry to the sea a considerable annual load of mineral matter in solution, and although, perhaps, a large proportion of this is contributed by underground waters issuing at the surface as springs, a certain but indeterminate portion of it must represent matter dissolved on the surface by moist air and rain. The English rivers, it has been computed, lower their basins 1 foot in about 13,200 years by solution alone, but it should be noted that estimates of this kind when based on the total annual quantity of dissolved matter carried to the sea are liable to be misleading, as there seems at present to be no means of ascertaining what proportion of the dissolved matter is due to underground dissolution and what to superficial.

CONSTRUCTIVE WORK OF RIVERS.

Hitherto we have regarded streams and rivers as merely agents of erosion; but they are not always destructive. In some circumstances they may also be constructive. As a matter of everyday observation we know that streams and rivers gradually fill up the basins of the lakes into which they drain with piles of fluviatile drift, sand, and mud. This infilling of lake-basins is relatively rapid in the case of valley-lakes fed by torrential alpine rivers.

The heavier and coarser gravels are shot into the head of the lake, where they fall to the bottom almost at once, forming sheet after sheet of the inclined beds that always mark the arrangement of fluviatile drifts discharged into still water.

The finer sands and silts are spread as a sheet over the floor of the lake, and as the infilling progresses, this sheet is covered over with the inclined coarser drifts as shown in fig. 15.

When the lake is completely filled up a *flood-plain* is formed, on the surface of which the river now flows towards the sea.

As the barrier at the lower end of the basin becomes worn down, the river with the greater slope thereby obtained once more becomes destructive. It now begins to cut away and remove the material it previously laid down, and in this way the dissection of the flood-plain is effected. It is seldom that the whole of the gravel infilling of the basin is completely removed during this period of destruction. Commonly we find that benches of gravel have escaped destruction in various places around the margin of the lake-basin, not only at the original level of the flood-plain, but also at the different levels at which the river temporarily established itself during its cycle of erosion. These gravel benches or *terraces* are a striking feature of alpine valleys in many lands.

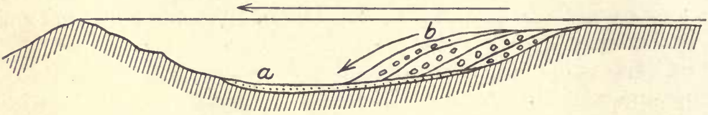

FIG. 15.—Showing filling of lake-basin by river detritus.
(*a*) Sand and silt. (*b*) Coarse drift.

Many of the great alpine lakes of New Zealand have been completely filled up with fluviatile drifts; and all the existing lakes are being rapidly reclaimed by the piles of detritus unceasingly shot into them by the torrential rivers that drain the neighbouring alpine chains.

The finer sediments discharged into a lake are sorted and spread out over the floor in a succession of parallel layers or beds that in a general way conform to the contour of the bottom. Such deposits are coarsest near the edge of the lake and finest near the middle and towards the lower end. The remains of freshwater fish, mussels, and other molluscs, of land animals, of tree-trunks, twigs, and leaves are frequently found in consolidated lacustrine sediments.

Besides filling up lake-basins, rivers frequently discharge enormous masses of detritus on to the sea littoral, whereby in time

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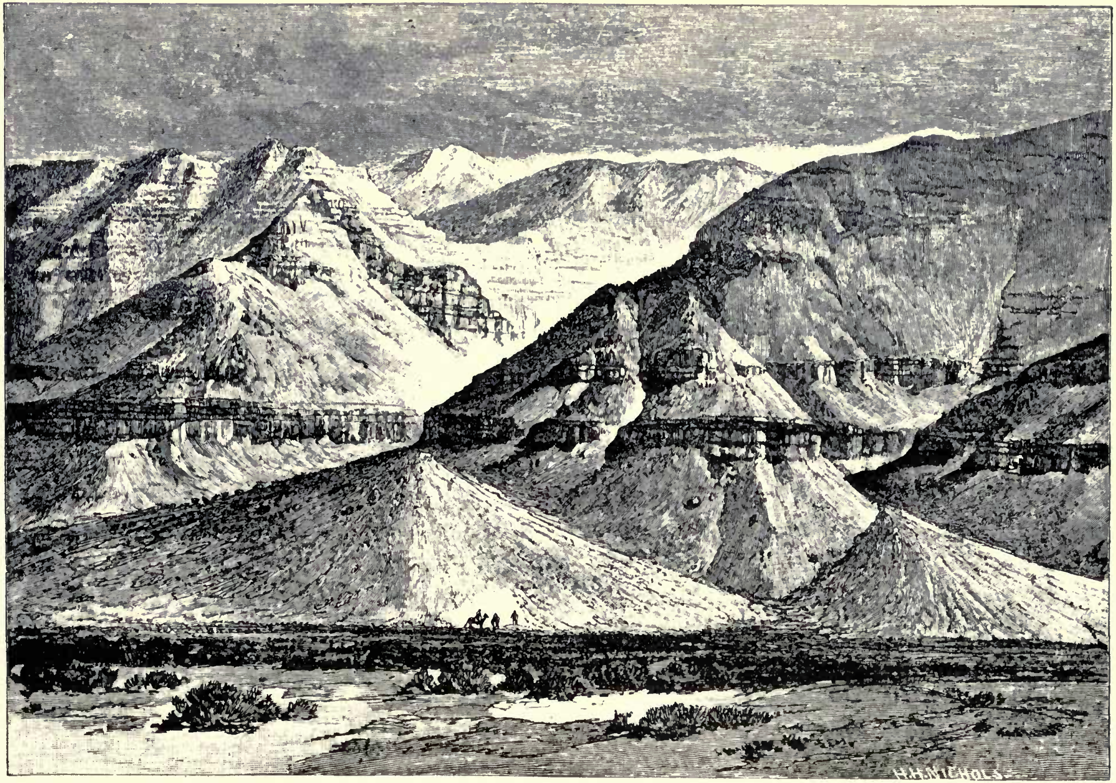
[Plate VIII.



Alluvial Cones. (After C. E. Dutton, U.S Geol. Survey.)

wide belts of land are reclaimed from the sea. Much of the land thus reclaimed is of a deltaic character. The celebrated Canterbury Plains in New Zealand are composed of gravel, sand, and mud shot into the sea by the large torrential rivers that drain the alpine chain. They are over 100 miles long, and vary from 20 to 50 miles wide. The low-lying deltaic plains reclaimed from the sea by the Yang-tse-Kiang, Ganges, Congo, Nile, Mississippi, and Amazon amount to many thousands of square miles.

River-Fans.—Many lateral mountain streams at the point where they emerge from their narrow defile gradually pile up their load of sand, gravel, and rocky detritus in the form of a wide-spreading *fan*, which may in time encroach so far over the floor of the main valley as to push the trunk river against the opposite wall. Good examples of river-fans may be seen in most mountain valleys where the rainfall is abundant and the denudation rapid.

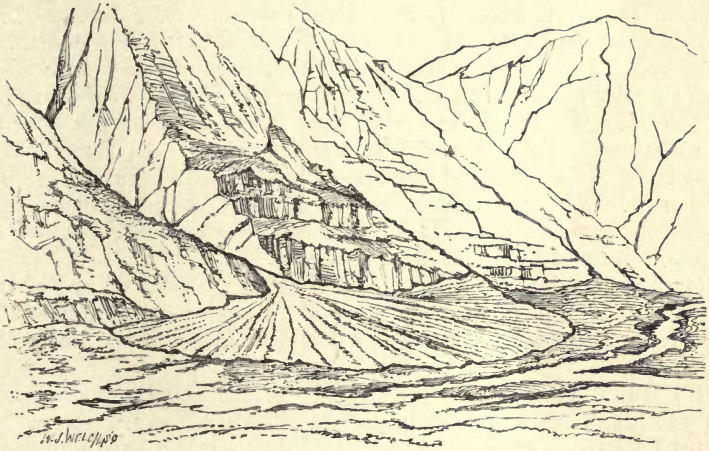


FIG. 16.—Fan at Tigar, Ládakh. (After Drew.)

Detrital fans of great extent are frequently piled up on the seacoast by mountain streams, and a number of such confluent fans may form wide coastal plains like the Canterbury Plains in New Zealand.

SUMMARY.

(1) A portion of the rain that falls on the surface of the land soaks into the rocks and soil, but another and larger portion flows over the surface, at first forming streamlets that eventually unite and form brooks. The confluent brooks as they descend the slopes

form large streams and rivers. The ultimate destination of most rivers is the sea or a lake, while a few die out in sandy deserts.

(2) The streams and rivers in their haste to reach their *base-levels*, which is the sea or some large lake, wear away all obstructions that lie in their path; and sweep before them all loose particles and rocks that tend to obstruct their downward course. The steeper their slope the greater is their velocity of flow; and the greater their velocity and volume the greater is their eroding and transporting power.

(3) Pure water is a nearly perfect lubricant; consequently it possesses little or no abrasive power. But the loose particles of rock and boulders transported by the flowing waters rasp and abrade the obstructing rocks which are thus worn away. The transported particles do not escape damage in this continual warfare. Like the rocks which they abrade they also are abraded and thereby reduced in size. Moreover, the mutual wear and tear of the heavier material as it rolls over and over along the floor of the channel reduces the size of the fragments. In these ways, that is by the attrition of the obstructions and the mutual chafing and grinding on the river-floor, we find that angular blocks are rounded, boulders are reduced to the size of pebbles, pebbles to sand, and, finally, sand to silt and mud.

(4) The heavier particles are rolled along the floor or bed of the stream, while the lighter are carried in suspension. Hence the heaviest material travels the shortest distance, and the finest the furthest.

(5) Running water in the form of streams and rivers therefore acts as (*a*) an agent of erosion, and (*b*) as an agent of transport.

(6) Soft rocks are eroded more rapidly than the hard and more resistant.

(7) When a plateaux is occupied by a formation crowned with a hard stratum, the wearing away of the softer underlying layers of rock enables a stream or river draining the plateaux to excavate a gorge.

At the point where the stream plunges into the gorge there is generally a waterfall or series of cascades. The rate at which the recession of the waterfall takes place depends on the rate at which the hard protecting cornice is undercut and worn away.

(8) When flowing across alluvial plains streams and rivers possess an inveterate tendency to deviate from the straight course. They generally meander across the plain in a winding course consisting of many loops and bends. The winding of streams is due to the slow rate of flow which enables obstructions, even those of the feeblest kind, to divert the stream from its course.

(9) The greatest erosive effect of a stream is on the concave bank, which is commonly the steeper for this reason.

(10) The total effect of all the subaerial processes of denudation is to reduce the general level of the land. If denudation were continued long enough, without compensating uplift, the land would be in time reduced to a condition of low relief not much above sea-level.

(11) A river with the aid of its affluents tends to reduce the level of the land within its drainage area. Throughout the infantile and youthful stages its denuding effect is ever increasing, and this is continued up to maturity. Through continued denudation in the uplands and constructive work in the lowlands, the gradients become less and less until a time is reached when the sluggish waters no longer possess any transporting power. This period of enfeebled denudation is termed the *decadent* stage. When denudation practically ceases, the land having been reduced to a plain or *peneplain* of low relief, the river is said to have reached its *base-level.*

If an uplift of the land now sets in, the decadent river system would be rejuvenated, and the more rapid the uplift the greater will be the denuding activity. In this way the peneplain previously formed will become dissected, and if denudation continues long enough, a second peneplain lying at a lower level will be carved out of the first.

(12) Peneplains may be also formed in elevated arid regions by long-continued exposure to the action of rain, frost, wind, and changing temperature. The elevated plateaux of South Africa and Australia were probably formed in this way.

(13) One of the local effects of rapid river-erosion is *stream-piracy.* When a stream cuts back its course more rapidly than a neighbouring stream, it may work its way across the divide and annex the head waters of the other stream.

(14) Sheets of basalt frequently afford effective protection to softer underlying rocks.

(15) The rate at which the whole surface of the land within a given watershed is worn away by the united processes of denudation is extremely slow. In England it amounts to about 1 foot in 3000 years.

(16) Although mainly destructive, rivers are also constructive. For example, they fill up lake-basins, and reclaim large maritime belts of land from the sea. The Canterbury Plains in New Zealand are a striking example of sea reclamation by fluviatile drifts.

CHAPTER V.

SNOW AND GLACIERS.

The present glaciation of the polar regions and of some alpine chains is a survival in a diminished form of the glaciation of the *Great Ice Age*, which reached its maximum severity in the Pleistocene, the period which immediately preceded the time in which we now live.

In the Great Ice Age the greater portion of North America and Northern Europe was covered with an invading sheet of polar ice. At the same time large portions of South America, Australia, Tasmania, and New Zealand were covered with huge glaciers and ice-sheets.

The best evidences of ice-erosion are found in the regions that were overrun by ice in the Great Ice Age.

Distribution of Glaciers and Snowfields.—Permanent snowfields and glaciers exist in the polar regions of both hemispheres, and elsewhere among the higher mountain-chains where the annual mean temperature is below the freezing-point.

Snowfields of less permanency are found in more temperate latitudes, and on the lower slopes of high ranges. They mostly disappear with the advent of spring and summer. The line above which the snow remains unmelted throughout the year is termed the *snowline*. At the poles the snowline comes down to the sea. In the lower latitudes it gradually rises till it attains its greatest altitude in the tropics. On the northern slopes of the Himalayas it is 19,000 feet above the sea, and in the Andes 18,000 feet.

The Action of Snow.—Snow as a geological agent is both (1) *protective* and (2) *destructive*.

Protective Effect.—As a winter covering on the foothills and flat slopes, snow protects the ground and vegetation from the action of frost and rain.

Destructive Effect.—When snow accumulates on steep slopes it slides down, and in doing so dislodges obstructing masses of rock and furrows the soil, pushing all loose material before it. A good deal of broken rock and soil is also picked up by the frozen snow, by which it is carried from a higher to a lower level. In this way *screes* of angular shingle, frequently of considerable magnitude, are piled up at the lower limits of melting snowfields.

Where snowfields descend to the edge of a precipice or accumulate on steep mountain slopes, large masses become detached in spring and summer and rush down as *avalanches* that sweep trees, soil, rock, and all movable obstructions before them.

Avalanches are frequently compelled by the contour of the ground, down which they bound with crashing leaps, to follow the same route year after year. In such places they are found to have carved out for themselves deep gulches in the solid rock. Such gulches resemble gigantic chutes and are known as *avalanche slides* (fig. 17). Their sides are frequently walled in with banks of rocky debris torn from the floor by the masses of semi-frozen snow as they thunder down to the valley below.

Streams may be blocked or partially dammed by masses of snow that have fallen from the heights above. In 1870 a large avalanche that fell from Mount Aspiring in the Alps of New Zealand blocked up the bed of the Upper Matukituki River for several months, and even after the barrier was breached masses of ice remained in the valley for two whole years.

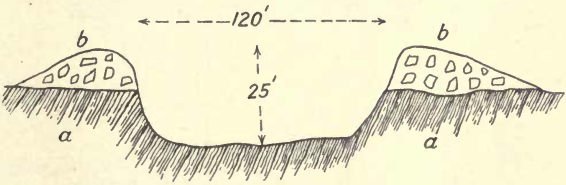


Fig. 17.—Showing cross-section of avalanche slide on slopes of Ben Ohau Range, N.Z.

(*a*) Bed rock of slate and sandstone. (*b*) Piled-up debris.

When the winter snows melt rapidly in spring and summer, as they frequently do in temperate climates under the influence of warm rains, they may cause a sudden inundation of the snow-fed rivers, the erosive and transporting power of which is thereby enormously increased for a time. Again, in arid regions bounded by snow-clad mountains, many of the streams and rivers, as in Central Otago, New Zealand, are entirely dependent for their summer flow on the supply of water derived from the melting snows and icefields at their sources.

Glaciers and Ice-Sheets.

The Motion of Glaciers.—Glaciers are composed of compressed snow, to which the term *névé* is usually applied. They are nothing more than *rivers of ice* fed by the snowfields lying on the summits and slopes of the adjacent mountains.

Ice possesses all the properties of a viscous body; hence, when it accumulates on the floor of a sloping valley, it descends or flows under the influence of gravity. Where the valley is wide it spreads itself out like a river, and where it is narrow it gathers itself together just as a river does in flowing through a gorge. It flows like pitch placed on a sloping plane, and accommodates itself to all the inequalities of its bed.

The rate of flow of water and ice is alike mainly dependent on the amount of precipitation and the gradient of their bed. Thus, while the flow of rivers may vary from 1 to 15 miles an hour according to the steepness of descent, that of glaciers is found to vary from 1 foot or less to 70 feet a day.

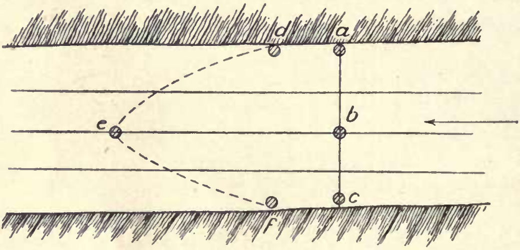


FIG. 18.—Plan of glacier showing differential surface flow. Extent of flow in middle, *b e*; and at the sides for the same unit of time, *a d* and *c f*.

On account of its comparative rigidity and the enormous pressure exerted by the moving mass of ice behind, a glacier will surmount and ride over all hummocks and projecting spurs that lie in its path. A glacier is thus able to pluck blocks of rock from its bed and leave them, when it retreats, perched high up on the valley slopes. For example, the ancient Wakatipu glacier in New Zealand tore off large masses of Tertiary limestone at the edge of the lake of that name, carried them nearly twenty miles and left them stranded on the schist slopes of Ben Lomond, nearly 2000 feet above the parent rock.[1]

The flow of a glacier, like that of running water, is greatest at the upper surface near the middle of the stream of ice, and least at the bottom and sides where the friction and drag are greatest.

A striking result of this inequality of flow is the formation of *crevasses* which commonly run transversely across the longest axis

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[1] Geology of Queenstown Subdivision, *N.Z. Geo. Survey Bulletin*, No. 7, p. 28.

of the glacier. The differential flow is also responsible for the banded structure of glacier-ice termed *névé-stratification*, and for the semi-bedded arrangement of the rocky debris frequently seen among the material piled at the terminal face.

What is meant by the differential surface flow will be easily understood by referring to fig. 18. Let us suppose that *a*, *b*, and *c* represent three blocks of stone or marks placed in a line across the glacier. It will be found that in the time it has taken blocks *a* and *c* to reach points *d* and *f* respectively, block *b* will have travelled to point *e*. Blocks *a* and *c* have moved slower than *e* because the flow of the ice which carried them has been retarded by the drag or friction of the rocky walls of the valley.

Referring to fig. 19, we find that while block *b* on the surface of the ice has travelled from *b* to *e*, block *p* on the bottom has in the same time travelled only from *p* to *s*, the slower rate of travel being due to the friction of the bed-rock.

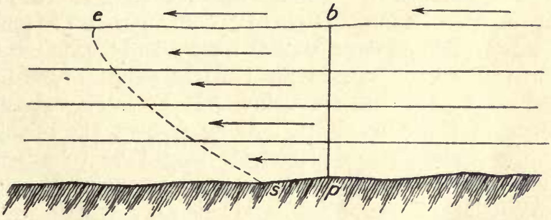

FIG. 19 —Longitudinal section of middle of glacier showing differential flow as between surface and bottom. Extent of flow at surface, *b e*; and at bottom, *p s*

It is obvious that the greater the drag or frictional resistance the greater will be the difference of flow as between the centre and the bottom and sides of the stream of ice.

Effect of Precipitation and Temperature.—The size of a glacier depends on the amount of precipitation and the temperature. With an increase of precipitation, or a decrease of temperature, the glacier will advance; and, conversely, with a decrease of precipitation, or an increase of temperature, the glacier will retreat. When the precipitation and the temperature act in the same direction there will be an acceleration of the advance or retreat.

A good example of the effect of varying precipitation is seen among the glaciers that descend from the New Zealand Alps. On the west side of the chain, where the precipitation is excessive and the slopes steep, the Fox glacier, 9·75 miles long, and the Franz Josef glacier, 8·5 miles long, descend within 670 feet and 690 feet of the sea respectively, in 43° and 44° of south latitude corresponding to the latitude of Boston in North America and Marseilles in South France. On the east side of the alpine divide, where the precipitation is about half of that on the west side, and the gradient of the valley-floors flatter, none of the glaciers descend below 2350 feet above the sea. The terminal face of the Tasman glacier, 19 miles long, is 2354 feet above the sea, but the thickness of the ice below that level is unknown.

Greater Summer Rate of Flow.—The flow of glaciers and ice-sheets is faster during the day than at night, and during the summer than in winter. The reason for this increase is still obscure, but it probably arises from the greater temperature during the day and in summer causing expansion of the surface layers of ice as compared with what they are at temperatures below 32° F.

The lineal coefficient of steel is 0·0000063 and of ice 0·0000528. Hence with a rise of temperature of 10° F., a strip of steel as long as the Tasman glacier, say 10,000 feet, would expand 6·3 feet, while a strip of ice the same length would expand 52·8 feet. Ice maintained at a temperature below 32° F. must expand under the influence of the sun's heat. Being free at the terminal end, the effect of expansion on glacier-ice would be to augment the normal flow due to gravity. The pressure of the valley-walls would prevent lateral expansion, and this may explain the arching of some 10 feet which is reported to take place on the surface of the Tasman glacier during the summer months.

Glacier Tongues.—Prolongations or tongues of ice that extend beyond the limits of the main body are of frequent occurrence along the margin of continental and Piedmont ice-sheets. Many good examples of these may be seen on the sea-front of the great glaciers that descend to the coast-line of Greenland, fed by the inland ice-sheet. But the most notable are found in the Antarctic region. One that has become well known in connection with Antarctic exploration is Glacier Tongue, near Hut Point, in M'Murdo Sound, South Victoria Land. It is a narrow, elongated, somewhat tabular mass of ice that stretches 5 miles into the sea. Where it rests against the land it is about a mile wide, and at its sea end about half a mile. Its height above the sea varies from 20 to 100 feet. The great depth of water obtained by soundings off the sea-end led Professor David to conclude that a considerable portion of the tongue must be afloat.[1] Some distance further north, the Nordenskyjold and Drygalski ice-tongues extend over the sea 20 and 30 miles respectively.

Mountain glaciers that lie in basins guarded by projecting spurs or buttresses of hard rock frequently terminate in narrow pro-

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[1] *The Heart of the Antarctic*, E. H. Shackleton, ii. p. 284, 1909.

longations or *snouts* of ice that may extend far beyond the portals of the ravine.

Distribution of Glaciers.—Glaciers occur at sea-level in the polar regions, but passing towards the equator they are found at gradually increasing elevations.

A great ice-sheet covers the whole of Greenland except a narrow fringe around the coast. Long tongues of ice descend to the sea in the valleys and sounds.

The icefields of the Antarctic are even more extensive than those of the Arctic. They everywhere descend to sea-level, and even extend over the surface of the sea for many hundreds of miles. The ice is so thick and spreads over the sea so far that the limits of the dry land cannot be ascertained. The *Great Ice Barrier* that fringes South Victoria Land is believed to have extended at one time far north of its present limits.

Valley-glaciers of great size exist at the present day in Alaska, Scandinavia, Alps, Himalayas, and New Zealand.

Among the most notable glaciers in the globe we have the following :—

In Alaska the *Malaspina* glacier, 30 miles long, descending from Mt. St Elias, with sea-front over 50 miles long.

In Greenland the *Humboldt* glacier with sea-face, 45 miles long, presenting ice-cliffs from 300 to 500 feet high.

In the Swiss Alps the *Aletsch* glacier, nearly 10 miles long, or, with snowfields, 15 miles ; mean breadth, 1⅛ mile : the *Mer-de-Glace* descending from Mont Blanc, 9 miles long.

In the Himalayan Mts., India, *Biafo* glacier, 36 miles long.

In New Zealand the *Tasman* glacier, 18 miles, or, with snowfields, 21 miles ; mean breadth, 1¼ mile.

In South Victoria Land the *Beardmore* glacier, of unknown length, deploys on to the Great Ice Barrier ; the Farrar glacier.

The glaciers of the Arctic, Antarctic, and Northern India, in the Karakoram Mts. are grouped as glaciers of the first order ; and those of New Zealand and Southern Europe of the second order.

Valley glaciers are fed by *summit-glaciers* and snowfields that sometimes descend gentle slopes to the main glacier, and sometimes where the slope is steep tumble down in a cascade of broken blocks of ice, forming what is known as an *ice-cascade*.

Glaciers that push their way to the sea break up at their terminal end into masses that float away as *icebergs*.

When a number of glaciers deploy from the mountains and unite, they form what is termed a *piedmont* glacier or ice-sheet.

Of such a nature is the great Beardmore glacier in South Victoria Land in the Antarctic and the Malaspina glacier in Alaska.

Confluent glaciers of this kind covered a large portion of Northern Europe and America in the *Pleistocene* or *Great Ice Age*.

The Surface Features of Glaciers.—The surface of glaciers is seldom smooth. More often it is rough, broken, and hummocky, and covered more or less with rocky debris. Moreover, glaciers that occupy valleys with steep gradients are generally crevassed in all directions by the unequal tensions set up in the body of the ice by the differential rate of flow.

Ablation of Glaciers.—The surface and terminal end of a glacier are subject to the heat of the summer sun. The daily rise of temperature causes the melting of the surface ice. This surface melting or *ablation*, as it is called, may amount to many feet in the course of a single year. Desor has estimated the mean ablation of the Swiss glaciers at 10 feet a year. The surface measured rate of melting of Alaskan glaciers varies in summer from 1 to 7 inches a day, all on retreating glaciers.

The effect of continued ablation on the upper surface is well seen in the formation of what are known as *ice-tables*. These are ice-pillars capped with a flat slab of stone. The stone protects the ice below it from the direct rays of the sun, with the result that, while the surrounding ice is melted away, a pillar of ice remains, growing taller and taller until it eventually becomes too slender to support its protecting cap.

The portions of a glacier covered with morainic debris are generally higher than the portions free from debris, the former being protected from ablation by their load of rocky material.

Ablation at the terminal face causes an apparent recession of the glacier. When the rates of melting and flow are equal the glacier remains stationary. But when the rate of melting is less than the rate of flow, the terminal end advances, and when more, it recedes.

Glacier-River.—Every valley-glacier is drained by a river which generally issues from an ice-tunnel at the terminal end of the glacier. Except in the polar regions this river flows summer and winter, but the winter flow is always much less than the summer. Its waters are at all times charged with a large amount of suspended silt.

The outflowing water is partly derived from springs issuing from the rocks within the drainage area of the glacier and its snowfields, but mainly from the melting of the glacier-ice.

During the summer months the surface of the ice is melted, the ice-water finding its way into every crack and fissure in the *névé*. Much of this water sinks to the bottom of the glacier, whence a portion of it soaks into the ground, while the remainder gravitates as small englacial streams towards the river draining the glacier-bed.

The internal heat of the Earth is conducted to the surface in all parts of the globe. This heat comes in contact with the base of the glacier and melts the ice at an estimated average rate of about one-fourth of an inch a year.

The pressure exerted by a moving body, such as a mass of ice, represents the expenditure of mechanical energy which is not lost, but transformed into heat. When the foot-lbs. of energy are known, the equivalent calorific value can easily be determined. The pressure lowers the melting-point of ice, so that in the case of thick sheets the melting-point will be sensibly less than 32° F.

It has been proved experimentally that every atmosphere of pressure (14·7 lbs. per square inch) lowers the melting-point 0·0133° F., which means that a pressure of 1103 lbs. per square inch will lower the melting-point 1° F. Taking the specific gravity of ice at 0·918, we find that to obtain a pressure of 1103 lbs. per square inch we require a sheet of ice 2775 feet thick.[1]

In other words, the melting-point at the base of a glacier 2775 feet thick will be 1° F. less than 32° F = 31° F. And since the pressure is proportional to the depth, it follows that for a thickness of 5550 feet the melting-point will be 2° less = 30° F. Therefore, as a near approximation, we may say that for every mile thick of ice the melting-point is lowered 2° F.

Agassiz proved by numerous experiments in a hole sunk to the depth of 200 feet in solid glacier-ice that the temperature at that depth was only 31·24° F. when the surface temperature was at freezing-point.

Hence it is assumed that in all thick glaciers the temperature of the base of the ice is constantly maintained at melting-point.

Retreat of Glaciers.—In certain circumstances the rate of retreat of a glacier may be not less rapid than the rate of advance. The Barry glacier in Harriman Fiord, Alaska, retreated 3½ miles between 1899 and 1910; and approximately 600 feet of this retreat took place in the year 1909–1910. Most existing glaciers in both hemispheres are shrinking in size.

The glaciers in Jakutat Bay, Alaska, show clear evidence of

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[1] $\frac{0{\cdot}0133}{1} \times 14{\cdot}7 = 1103$ lbs. per sq. in.; S.G. of ice = 0·918; weight of a cubic foot of water = 62·32 lbs.; therefore pressure of 1 foot of water = 0·433 lb. per sq. in., as $\frac{62{\cdot}32}{144} = 0{\cdot}433$. Therefore pressure of 1 foot of ice = 0·433 × 0·918 = 0·397 lb. per sq. in. And 1103 lbs. ÷ 0·397 = 2775 feet of ice for 1° F.

three periods of temporary advance during the general recession now in progress. The last advance, in 1906, was short and spasmodic, and has been not unreasonably attributed by Tarr and Martin[1] to the unusual supply of snow and ice shaken down from the mountains by the great Jakutat earthquakes in September 1899. On account of the slow rate of flow, the terminal end of the glaciers did not respond to the new impulse until six years had elapsed, and naturally the shortest glaciers were the first to be affected.

Geological Work of Glaciers.

Glaciers as agents of denudation perform a twofold office. They (1) transport material from a higher to a lower level; and (2) they degrade the land by eroding the bottom and sides of their bed.

Glaciers as Transport Agents.—A valley-glacier may transport material (*a*) on its surface; (*b*) scattered throughout the body of the ice; or (*c*) dragged along the floor.

The surface load may find its way on to the glacier in various ways. Among the higher mountain-chains where glaciers exist the frosts are very severe. The winter frosts break up and shatter the rocks forming the valley-walls. The fragments and masses thus broken may form *talus* deposits that slowly slide down on to the edge of the glacier; or, when assisted by gravity on steep slopes, they may fall on to the ice as soon as they are detached; or they may be carried down by avalanches; or transported from the heights above by the snowfields that feed the glacier at its sources.

The rocky load that lies on the surface of a glacier, or accumulates at the end, may be *lateral*, *medial*, or *terminal*, according to the position it occupies.

The debris that falls on to the sides of the glacier forms marginal belts or *lateral moraines*.

When two glaciers from adjacent valleys unite, their inner lateral moraines come together and form what is called a *medial moraine* (figs. 20, 21).

When more than two glaciers unite, the surface of the trunk glacier may carry several belts of medial moraine, although the position of these will not be quite medial.

At the place where the glacier ends, that is the *terminal face*, the surface debris is tipped over and piled up in a pell-mell fashion. Where it falls into the glacier-river it is washed away and soon becomes rounded and water-worn.

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[1] R. S. Tarr and Lawrence Martin, "The Earthquakes of Jakutat Bay, Alaska, in Sept. 1899," *Prof. Paper* 69, *U.S. Geo. Survey*, 1912.

A large proportion of the rocky surface load falls into the crevasses and thus becomes engulfed in the body of the ice. This, with much of the debris carried down by the tributary snowfields, forms the *interglacial* load of the glacier.

The material broken up by the pressure and grinding action of the moving ice, or plucked from the bed and carried forward along the floor of the valley at the base of the glacier, is termed *subglacial.*

Fig. 20.—Medial moraines, Mer-de-Glace.

The interglacial and a portion of the subglacial debris is carried down to the terminal face, where it is piled up with the rocky material tipped from the surface moraines. A large portion of the subglacial debris is washed away by the glacier-river.

The material composing the surface moraines consists mainly of angular blocks of all sizes, ranging up to masses 200 tons or more in weight, mixed with small angular fragments and clay. A few of the blocks show striated surfaces produced by the stones rubbing against one another, or by rubbing against the valley-walls when frozen in the moving ice.

The interglacial debris is frequently arranged in layers lying parallel to the *névé* foliation. This foliation is frequently very minute, and is always very striking where layers of clean ice alternate with layers of earthy matter. These dirt layers are frequently inclined at steep angles, the inclination being generally towards the head of the glacier. In some glaciers, particularly near the terminal face, the layers are sharply folded and contorted, due to the differential flow of the upper and lower layers of the ice.

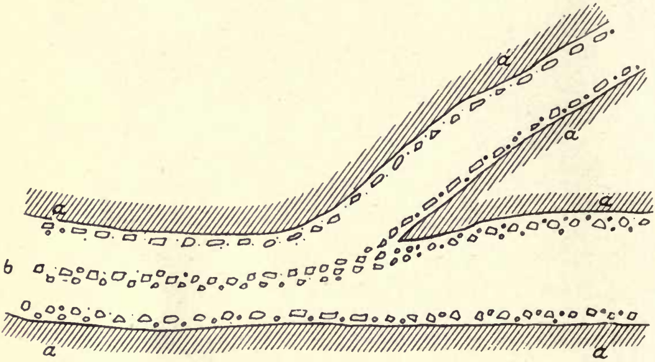

FIG. 21.—Showing lateral and medial moraines.
(*a*) Lateral moraines. (*b*) Medial moraine.

Many glaciers that are quite free from morainic matter in the upper portion of their course are covered with rocky debris at their lower end. This material, which sometimes appears in patches and sometimes as a continuous sheet across the whole width of the ice, is subglacial and englacial debris that has found its way to the surface partly owing to the culminative effects of long-continued surface ablation, and partly owing to the upward flow of the lower layers of ice due to pressure and the obstructing apron of debris in front.

There is abundant evidence in Alaska and Spitsbergen that glaciers which have crossed an arm of the sea have picked up marine material from the sea-floor and transported it over the land lying in the path of their advance. It was doubtless in this way that the shelly glacial drifts of North-Western Europe were spread by the ice-sheets of the Glacial Period over the land surrounding the sea-basins.

Glacier-Drifts (fig. 22).—At the terminal end of valley-glaciers we thus find two classes of matter, namely, the angular rubble transported by the ice, and the more or less water-worn drifts transported by the glacier-river. Both classes are mixed at certain points, and they form what are termed *fluvio-glacial drifts.*

Ground-Moraines.—The broken-up rock and clays that accumulate under a glacier or sheet of ice, as well as all the drift that is deposited beneath the advancing ice, constitutes what is termed *ground-moraine, boulder-clay,* or *till.*

The thickness of the ground-moraine is notably irregular. It may vary in a hundred yards from a few feet to many hundreds of feet. The distribution is equally variable, but for the most part subglacial deposits of this kind are principally developed in the lower end of glacial valleys and in depressions among the foothills. Subglacial drifts are sometimes present on ridges and absent in the neighbouring low ground and valleys.

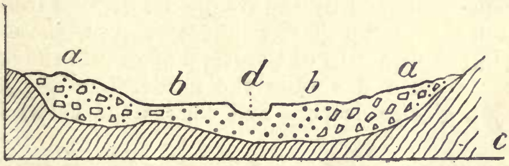

Fig. 22.—Section of glacier-valley.

(*a*) Glacier moraines. (*c*) Basement rock.
(*b*) Glacier gravels. (*d*) Glacier-river.

When the boulder-clay occurs in long ridges, as it frequently does in the lower foothills, it forms what in Scotland are called *drums* or *drumlins,* that run in the general direction of the rock-striation or ice-movement.

The *till* of Scotland varies from 0 to 160 feet thick, and that of North America from 0 to 500 feet. In Germany the Pleistocene glacial drift varies from 0 to 670 feet thick. In Greenland there are enormous accumulations of ground-moraine on the edge of the inland ice at Austmannatjern, where there are no *nunataks,* and not a vestige of surface moraine visible.

Nunataks are peaks of rock projecting above the level of an ice-sheet or ice-plateau, and where they are absent it is obvious that no fragments of rock can be shed on to the surface of the ice.

Glaciers as Agents of Erosion.—When a thin sheet of snow lying on a steep mountain slope moves downhill, it heaps the loose shingle and soil on which it rests into small furrows that are not unlike those made by a harrow on cultivated land. This action cannot be described as erosion since the material is already loose and is merely displaced by the sliding snow. Even a thick snowfield will glide downhill without eroding its bed, except where a boulder is frozen into its base. In this case the boulder will furrow the loose material through which it moves, and scratch projecting rocks that lie in its path.

Large glaciers are capable of wearing away the surface of the rocks forming their bed by the pressure of their mass alone which amounts to 25·5 tons per square foot for every thousand feet of ice. When the pressure exerted by the ice exceeds the ultimate strength of the rock, the crumbling and erosion of the rock-surface must be the inevitable result. It is probable, however, that most of the erosion is effected by the fragments of rock frozen into the base of the ice. As the glacier moves onward, these fragments, being held in the firm grip of the ice, plough into the softer rocks, while they scratch and abrade the harder like a gigantic rasp. In this way a glacier deepens and widens the valley in which it flows.

The maximum thickness of the Greenland ice is estimated to be not less than 5000 feet, and that of the Antarctic probably much more. In the Pleistocene the ice is believed to have attained a thickness of 5000 feet in Scotland, 6000 feet in the Alps and Scandinavia, 7000 feet in New Zealand, and 8000 feet in North America. The erosive power of such masses of moving ice must have been enormous (Plate IX.).

It is, of course, impossible to watch the progress of the erosive work being carried on by existing glaciers; but if we examine a valley that has been at one time occupied by a glacier, we find that all the irregularities have been worn down, and that the bottom and sides are smooth or gently undulating. Hummocks of rock that lie in the valley-floor are found to be scored and furrowed, while projecting spurs are truncated. Where the glaciation has been prolonged and severe, rock-basins are found in the floor of the valley, and in many cases the neighbouring mountain slopes are excavated into benches or platforms.

No other natural agent than ice is known that could effect these changes; and when we find at the lower end of the valley huge piles of ancient morainic matter, then are we sure that moving ice was responsible for the work.

Country that has been at one time overrun by ice always presents smooth rounded contours and flowing outlines, except among the

To face page 66.] [Plate IX.

Glaciated Rock Surfaces. (U.S. Geol. Survey.)

higher mountains where the recent work of frost has shattered and broken up the ice-shorn surfaces. The most striking effects of glacial erosion are generally found in the valleys and foothills of recently glaciated countries.

All geologists are agreed as to the ability of glaciers to wear away and plane the surfaces over which they flow ; but all are not agreed as to the maximum amount of erosion they are capable of performing.

Many maintain that the erosive effects of glaciers are small and can never amount to more than the smoothing, scratching, and superficial planing of the rocks over which the ice flows. Glaciers, they contend, are incapable of excavating to any extent, but always occupy pre-existing valleys. Others are prepared to maintain that glaciers are not only able to excavate valleys but even to *overdeepen* them in certain circumstances.

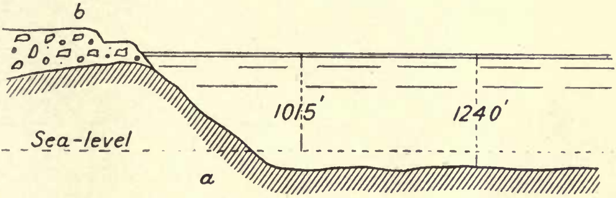

Fig. 23.—Section of lower end of Lake Wakatipu rock-basin, N.Z.
(*a*) Altered greywacke. (*b*) Kingston ancient moraine.

The truth probably lies between these extreme views. Recent investigation would tend to show that the present drainage systems in glaciated regions had been already determined at the advent of the *Great Ice Age*, and that the glaciers merely took possession of valleys already in existence. These valleys they widened and deepened, and in favourable situations *overdeepened*, so as to form the rock-basins of many of the mountain valley-lakes of the present day.

The enormous amount of *rock-flour* in the form of suspended matter annually transported from below a glacier by the glacier-river is satisfactory evidence of the wear and tear that is constantly going on under the moving river of ice.

Glacial Striæ.—Many of the blocks of stone in a ground-moraine are scratched and grooved with parallel *striæ* (fig. 24). Some boulders are striated with two systems of striæ, crossing each other at a more or less acute angle. This may mean that the first position of the block became changed in respect of the line of movement of the ice, thus permitting a second set of striæ to be scored on the face of the stone.

Striated stones, although most common in boulder-clays, are frequently found in the lateral moraines of existing glaciers.

The striæ are best preserved on granite, diorite, quartzite, greywacke, and all hard sandstones. Where the glacier flowed over such soft rocks as shale, chalky clays, marls, phyllite, slate, or mica-schist, striated stones are seldom or never met with in the subglacial debris. The striæ formed on basalts and all basic igneous rocks are soon effaced by weathering, as the felspar constituents of these rocks are acted on by atmospheric carbonic acid and moisture with comparative rapidity. Where the striated basaltic boulder has been embedded in impervious clay, the striæ may remain fresh and sharp for a considerable time.

Roches Moutonnées (fig. 25).—These are rounded, hummocky, or whale-backed bosses or ridges of hard rock that have been worn down by an overriding stream of ice. They generally occur on the floor of ancient glacial valleys and on valley slopes, but some beautiful examples are found at high altitudes, as, for example, near the summit of Mount Rosa in New Zealand, at a height of 5500 feet above the sea and 3000 feet above the Hooker Glacier.

FIG. 25.—Showing *roches moutonnées.*

Erratics.—These are blocks of rock that have been transported by ice some distance from the parent rock. In some cases they have been carried from one watershed to another, and even from one country to another. The Scandinavian ice-sheet which flowed down the North Sea carried many foreign rocks from the frozen north and left them stranded on the shores and inland parts of England.

Perched Blocks.—Masses of rock that have been left stranded by the retreating ice on the summit of ridges or on the flanks of mountains are termed *perched blocks.* Some perched blocks have been transported many miles from their parent rock; and in many cases they have been left by the melting ice in prominent or precarious positions, hence the name.

Perched blocks (fig. 26) are angular or partially rounded according to the amount of wear and tear they have suffered

[*To face page* 68.

Fig. 24.—Showing ice-striated stone.

during their journey. When carried on the surface or in the body of the ice, they are angular, but when they were frozen into the base of the glacier and dragged along the rocky floor, they were generally smoothed, striated, and sometimes polished on the lower side.

One of the most noted perched blocks in Europe is the *Pierre à Bot,* a huge block of granite from the Mont Blanc range, stranded about two miles from Neufchâtel. It is estimated to weigh about 3000 tons.

Glacial Benches.—These may be, according to their origin, (*a*) *detrital* or (*b*) *rock-cut.*

Fig. 26.—Perched block, Arran.

Detrital Benches (fig. 27) are formed in parallel lines along the slopes of ancient glacial valleys. Two, three, or as many as twenty or more of these may rise on the mountain side one above another like a flight of gigantic steps. They are not horizontal, but slope at a low angle towards the lower end of the valley.

These detrital terraces are ancient lateral moraines that accumulated along the edge of the glacier. When the glacier shrunk in depth, the rocky belt of detritus was dropped on the mountain slope, and piled up in the form of a rubble platform or bench. At its next resting-place another belt of debris accumulated on the edge of the ice again to be deposited on the flank of the range as the melting ice shrank in depth, thus forming a second bench; and so on, other benches being formed in the same way so long as the glacier, by fits and starts, continued to shrink in its bed.

Glacial Rock-Terraces have been excavated out of the mountain slope forming the wall of the ancient glacial valley. Two, three, or many of these benches may occur one above the other. They are not so continuous as detrital benches nor is their inclination so uniform. They are more or less undulating in longitudinal section, and they vary considerably in width, this variation being due to the irregularities of the original slope in which they were excavated.

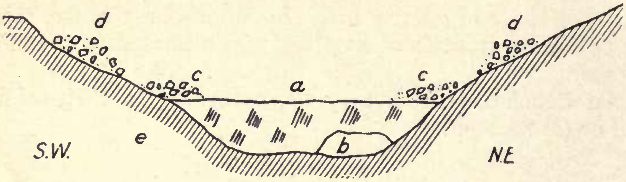

Fig. 27.—Showing rubble terraces now being formed on the edge of the Hooker Glacier, New Zealand.

(*a*) Glacier-ice.
(*b*) Glacier-river.
(*c*) Lateral moraines.
(*d*) Ancient lateral moraines forming rubble terraces.
(*e*) Greywacke and slaty shales.

Rock-cut terraces are only found in regions that have been subject to intense glacial erosion. A striking example of this kind of ice-erosion is seen on the slopes of Ben More in New Zealand, where more than thirty benches have been carved in the mountain slope between Lake Luna and the summit of the mountain in a height of about 3000 feet.

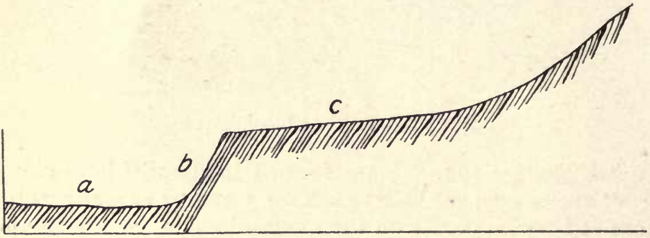

Fig. 28.—Showing truncation and planing of projecting spur.

(*a*) Floor of glacial valley. (*b*) Truncated end of spur.
(*c*) Crest of spur planed into a platform.

Spurs that projected into glacial valleys are generally found to have been truncated, and where the ice flowed over them their crest is in most cases planed down into a platform as shown in fig. 28.

Crag and Tail.—Ice-worn ridges usually present a long continuous

A. SHOWING DISSECTION OF ALLUVIAL PLAIN.

B. HANGING VALLEY. (After Tarr, U.S. Geol. Survey.)

slope in the direction from which the ice travelled, and a steep slope on the lee or further end where frequently a certain amount of rocky debris collected. This form of ice-erosion is known as the *crag and tail* and is well seen in fig. 25.

Fluvio-Glacial Work of Glaciers.—In another place we have seen that every valley-glacier is drained by a river which issues from an ice-tunnel at the end of the glacier. Glacier-rivers always carry a certain amount of suspended matter in the form of silt or rock-flour; and in the case of many ice-fed streams the amount of fine silt thus carried in suspension is so large that their waters possess a milky-white colour.

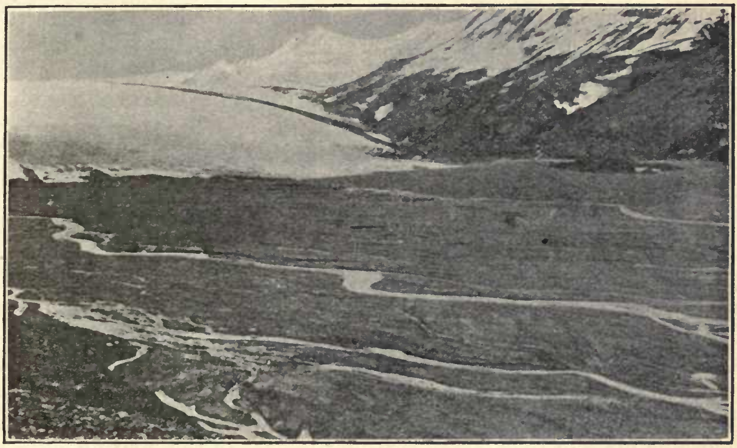

Fig. 29.—Valley-train below Hidden Glacier, Alaska. (After Gilbert, U.S. Geo. Survey.)

Besides rock-flour the river also transports sand and gravel derived from the bottom of the glacier. The coarser material, frequently mingled with angular morainic debris, is dropped first, further on the finer gravels, and lastly the sand and silt. In this way glacier-streams frequently build up alluvial plains called glacier *valley-trains*.

A *valley-train* (fig. 29) is thus a continuous sheet of *glacial drift*, graduating from the purely morainic drift at the head to the purely fluviatile deposit at the end. The material is always more or less stratified throughout, and in all of it, both coarse and fine, the angular blocks as well as the water-worn gravels have a common glacial origin.

Where the glacial river discharges its load into a lake or a bay, a delta is formed. In this way many valley-lakes have been filled, or partially filled, and large areas reclaimed from the sea.

When the outlet of a glacier-river has become blocked with some obstruction, such as an ice-fall or an accumulation of morainic debris, the flow of the river is checked, with the result that the transported load of sand and gravel can no longer be carried forward to the valley-train, but is deposited in the ice-tunnels of the subglacial streams. When the glacier retreats, these deposits of sand and gravel remain in the form of ridges that occupy the sites of the subglacial streams, their form, length, and height being determined by the form and size of the ice-tunnels which they filled.

Deposits of this kind frequently run parallel with the valley-walls. They are common in all recently glaciated regions. In the Central Plain of Ireland they are called *eskers*, and in Scotland *kames*. The sand and gravel of eskers are generally sorted into layers of coarse and fine material, and in this respect they cannot be distinguished from ordinary *river-drifts*.

At the time the confluent glaciers deployed from the alpine valleys and still occupied the low country and plains, numerous streams would doubtless issue from the melting front of the ice.

The ice-sheet would override the land, and its flow would be towards the sea independently of the minor irregularities of the contours. Hence the escaping waters would at first flow with little relation to the existing drainage lines. Streams would be discharged over hills and ridges as well as over the plains, walls of ice forming the enclosing barriers of the channels. Wherever they went these streams would leave a trail of well-worn glacial drift in the form of sand and gravel, with perhaps here and there a sporadic mass of rock dropped from the base of the melting ice.

It was probably in this way that the sheets of *plateau-gravels* of South Germany, Alaska, and New Zealand were formed. These high-level gravels are spread over plateaux, hills, ridges, and mountain slopes frequently without any relation to the present topography. In many places they fill up inland alpine valleys.

According to their situation they may merge into or overlie *boulder-clay*, morainic debris, marine sands, and raised-beach gravels.

These drifts are most striking when they form mounds which run across valleys and plains, or even over watersheds. Such mounds when found on plains or along hillsides constitute the eskers described above.

Topographical Effects of Glaciers.—A glacier or ice-sheet modifies the topography of the land over which it moves by its destructive effect as an agent of erosion, but its constructive effect as an agent of transport is not insignificant.

A valley-glacier in an alpine region deepens and widens the valley which it occupies. The extent to which the glacier is able to modify the original topographical features is dependent on the hardness of the country rock, the depth of the ice, the rate of flow, and the duration of the glaciation.

The cross-section of valleys that owe their existence to stream erosion is usually V-shaped; and the sides are generally rough and irregular. Glacier erosion usually changes the V-shaped form into a U-shaped one.

Where the valley traverses granite, gneiss, or other hard rock, its sides are frequently carved into approximately vertical walls; but in softer rocks the form assumed is commonly that of a U with its sides spread out in a gentle catenary curve.

Where the trunk glacier has deepened its bed more rapidly than the lateral tributary ice-streams, the valley-floor of the tributary streams is found to occupy a higher level than that of the trunk valley. Such *hanging valleys*, as they are called, are common in all recently glaciated regions. Many fine examples of *hanging valleys* are seen in the fiordland of Otago in New Zealand, in North America, and elsewhere (Plate X.).

The descent from the end of the *hanging valley* is frequently quite abrupt, with the result that the drainage of the lateral valley is compelled to find its way to the main valley in the form of a waterfall or cascade.

In fiordlands and in recently glaciated mountains composed of hard crystalline rocks, the cross-section of the valleys frequently shows two phases of formation—namely, a wide upper flat-bottomed valley and a lower narrow U-shaped valley excavated in the floor of the upper one. The portions of the floor of the upper valley that have escaped denudation form the terraces or mountain meadows known in Norway as *albs*. Small rock-cut basins or *tarns* are common features of these high mountain meadows.

We have already seen that the effect of moving ice is to wear away all the corners and minor irregularities of the landscape. The result of this planing down of the surface features is that a region recently overrun by an ice-sheet usually presents smooth flowing contours and a monotonous sameness of outline, dome-shaped hills, whale-backed ridges, and mammillated slopes everywhere meeting the eye.

The slopes of glaciated valleys are generally even, being free from projecting spurs and ridges; but where spurs do project into the valley they are usually truncated, and their crests planed down into terrace-like platforms.

All the recently glaciated valleys in New Zealand and many in Switzerland and Alaska have been *overdeepened* by the ice. The depressions thus formed are now lake-basins. The size and depth of many of these basins has been increased by barriers of morainic debris deposited at their lower end (fig. 23).

The head of glaciated valleys is frequently found to open out into a circular basin known as a *cirque,* on the floor of which there may be one or more shallow *corrie-lakes* (fig. 30) or lagoons occupying rock-cut basins. According to Professor Bonney's view, cirques occupy pre-glacial hollows cut by convergent streams with walls modified by ice erosion. Richter, on the other hand, maintains that they are the result of frost-shattering above the level of the ice. The frost dislodges masses of rock, which fall on to the ice and are carried away, whereby the formation of a talus is prevented. The ice protects the floor of the cirque, which is thus relatively flat, while the absence of a protecting apron or talus permits the frost to sap and wear away the walls until they become steep or even vertical.

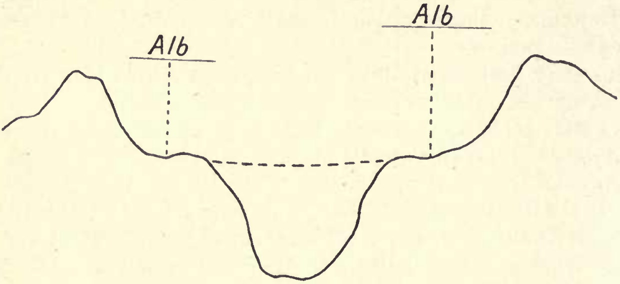

FIG. 29A.—Showing albs or mountain meadows.

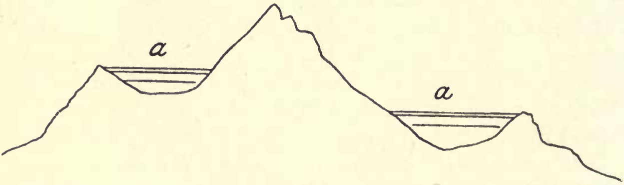

FIG. 30.—Showing cross-section of two cirques on opposite sides of a range. (*a*) Corrie-lakes.

Where two glacial valleys on opposite sides of a mountain-chain head together, as they so frequently do where the original valleys follow some powerful fault or line of structural weakness, the cutting back of the cirques may result in the removal of the dividing ridge, and in its place we find a plateau or flat saddle occupied by swamps or shallow lagoons.

Where one cirque lies at a lower level than the other, the lower by its recession is able to pirate the drainage of the higher, which is thus reversed or carried to the other watershed. Examples of *reversed drainage* are not uncommon in alpine New Zealand and North America. Much of the stream-pirating and beheading described in a preceding page has been doubtless accelerated, if not initiated, by ice-erosion.

Sharp-peaked mountains with excessively steep walls are frequently found in glaciated regions on the margins of ice-caps. Many good examples of these remarkable peaks, which are called *tinds*, have been developed on the margin of the Norwegian plateau glaciers. Mitre Peak in the fiordland of New Zealand is a typical example of a tind. Tinds have been obviously exposed to intense ice-erosion, and the conical shape which they frequently assume may not improbably be due to the shattering and exfoliation of successive layers of rock by frost action since the retreat of the ice-sheet.

The terminal debris of glaciers is frequently piled up in the form of hills and mounds disposed in crescent shape on the plains where the glacier deployed from its alpine valley, and although these morainic hills seldom exceed a height of 300 feet, they are nearly always a striking feature in the landscape, as they present a curious assemblage of hills and undrained hollows of the *knob-and-basin* type.

Crescent-shaped morainic mounds, one behind another, may be traced up an alpine valley, each mound marking a place where the glacier rested for a time during its final retreat. The highest mounds being the last formed are always the freshest.

The valley-glaciers of Alaska, Alps, Pyrenees, Himalayas, and New Zealand are but the remnants or stumps of great ice-streams that, during the Great Ice Age, descended from the mountains and spread over the neighbouring foothills and plains.

The freshness of some of the glaciated slopes and esker-mounds of sand and gravel in Scotland, Alaska, and New Zealand is often very striking. In many places the contours look so smooth and fresh that one is tempted to think they were moulded but yesterday, or that the forces of denudation must have been held in abeyance since the close of the Glacial Period. This freshness is all the more remarkable when we observe that contiguous areas occupied by hard rock have been deeply dissected by streams. This differential erosion is a common feature of all glaciated regions.

The preservation of the glaciated forms and mounds of morainic debris is believed to have been due to the protection afforded by permanent snowfields. It is contended that during and for some time after the recession of the ice, the refrigeration would still be sufficient to allow the formation of sheets of permanent or nearly permanent snow that would protect the ground on which they lay from subaerial waste or denudation, stream erosion being confined to the defined water-courses and lines of drainage.

The evidences of recent glaciation in the form of boulder clays, moraines, and erratics are not always conspicuous in regions that have been subjected to intense ice erosion. In Alaska and Antarctica during the maximum glaciation the great work of the ice was erosion with deposition of detritus off-shore; and, as in all intensely glaciated regions, the glacial deposits above sea-level are thin and scattered, and were mostly deposited during the ice retreat.

Glacier Lakes.—Ice-dammed lakes exist on the margin of the Frederikshaab ice-apron on the fringe of the Greenland ice-cap. One of these, the Tasersuak, 12 miles long and over 2 wide, stands at a height of 940 feet above the sea and is blocked by ice at both ends. It drains through a canal to a smaller lake at a height of 640 feet.

A glacier descending a steep tributary valley may by a sudden advance impound the drainage of the main valley and form a lake. Such a lake is necessarily short-lived, since the ice-barrier is soon destroyed. A remarkable case is that of the tributary glacier which blocked the Suru Valley in the Himalayas, in 1896, and held up the drainage until a lake over 20 miles long was formed. When the ice-barrier was broken through, the valley below was devastated for a distance of 40 miles.

More important is the case where the drainage of a tributary valley is held up by the glacier occupying the main valley. If the ice-barrier stands above the level of the pass or *col* at the head of the tributary valley, the drainage of the lake may be reversed, and the height of the col will represent the highest level to which the lake can rise. A typical example of a lake of this class is the well-known Märjelen See at the elbow of the great Aletsch glacier in the Alps. This glacier-lake is impounded in a tributary valley, and at one time drained over a low col into the adjoining valley occupied by the Viesch glacier. Such a lake, it is thought by some writers, might in time give rise to a detrital beach at the level of the col.

Ice-dammed lakes possess a peculiar interest in that they are believed by some writers to offer a satisfactory explanation of the origin of certain step-like detrital terraces that are a conspicuous picture in many recently glaciated regions. It was first suggested by Agassiz, and afterwards urged by Jamieson,[1] that the famous

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[1] *Quart. Jour. Geo. Soc.*, vol. xix. pp. 235–259, 1863.

Parallel Roads of Glenroy, in Argyllshire, are the beaches of fresh-water lakes that seem to have arisen from glaciers damming the mouths of the valleys and reversing the drainage. According to this view, each of the three terraces marks a temporary level of the ancient Glenroy lake. The terraces are perfectly horizontal, contour around the valley-walls, and occur at a height of 847 feet, 1059 feet, and 1140 feet above sea-level respectively.

The existence of ice-dammed lakes has been clearly demonstrated in New Zealand, North England, Scotland, North America (*e.g.* the glacial lake Agassiz), and other intensely glaciated regions; but there is grave doubt as to the ability of such glacier-lakes to explain the genesis of many of the remarkable tiers of glacial terraces that are such a prominent feature in the topography of Alpine New Zealand. Take a typical case. On the east side of the coastal range the walls of the main valley leading up to Burke's Pass are terraced nearly up to the crest, the remains of about forty benches being clearly discernible.[1] The valley opens on to the foothills at the back of the Canterbury Plains, and it is almost inconceivable that there ever existed in these low foothills a mass of ice of sufficient magnitude to form a barrier across the main valley and impound a glacier-lake at a height of 4000 feet above the sea. It seems easier to suppose that the terraces represent the lines of frost-shattered debris that collected on the edge of the plateau ice in the form of lateral talus-like aprons. Beautiful terraces of this kind have been recently formed by the Hooker glacier near Mount Cook. They contour round the valley-walls at different levels, and consist of angular rock-debris mingled with waterworn sands and gravel brought down by the small rivulets that drain the adjoining slopes. The Hooker glacier has been subject to alternating periods of rapid shrinkage and comparative rest. The lateral fringing terraces were obviously formed during the intervals of rest. A well-marked terrace has already accumulated at the present surface-level of the glacier. This glacier, it should be noted, is little more than the shrunken skeleton of the great ice-river that at one time filled the valley; and it illustrates, in a striking manner, the fact that a considerable retreat of the terminal face of a glacier is always accompanied by a corresponding shrinkage in depth. In other words, terminal ablation and surface ablation are contemporaneous and co-relative.

SUMMARY.

(1) Snow (*a*) protects the land on which it rests from the influence of frost, rain, and other subaerial agents of denudation;

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[1] J. Park, *The Geology of New Zealand*, p. 237, London, 1910.

and (*b*) it has a destructive effect when it falls or slides down steep slopes by carrying loose rocks from a higher to a lower level.

(2) Glaciers are found in the polar regions and in the higher alpine regions of temperate and warm latitudes. They flow like pitch or asphalt.

(3) Glaciers and ice-sheets are both *destructive* and *constructive.* They wear away the rocks over which they flow by their sheer weight, while the boulders frozen into their base plough into the rocks, which are thus scored and furrowed and in time deeply eroded or removed.

(4) Glaciers that are overlooked by mountains always carry a rocky load of debris partly on their surface, partly interglacial, and partly subglacial.

(5) The debris on the surface of a glacier is arranged in belts running parallel with the sides, forming *lateral* moraines.

(6) Where the glaciers unite, their adjacent lateral moraines form a *medial* moraine.

(7) The transported load when piled at the end of the glacier constitutes what is called a *terminal* moraine.

(8) The broken-up rock and clay that remains on the floor of a glacial valley after the ice has disappeared is termed a *ground* or *bottom* moraine, *boulder-clay*, or *till.*

(9) When the boulder-clay is piled up in ridges, often running parallel with the hillsides, it forms what are known as *drums* or *drumlins.*

(10) Many of the boulders found in ground-moraines are scored and striated, as also are hard bosses of rock that were overridden by the ice. Such ice-shorn bosses are called *roches moutonnées.*

(11) Large blocks of rock left by the melting ice in conspicuous places are termed *perched blocks.*

(12) Glaciers are drained by rivers which issue from ice-tunnels at the terminal end.

(13) Glacier-rivers carry a load of gravel, sand, and silt, which is spread out as a *valley-train* or deposited in a lake or sea.

(14) The contours of recently glaciated regions are smooth and undulating, all the irregularities and corners having been worn down. The V-shaped form of stream-valleys has been changed to a U-shaped form.

CHAPTER VI.

THE GEOLOGICAL WORK OF THE SEA.

THE sea covers about three-fourths of the surface of the globe. It is the destination to which most streams and rivers hasten, and the repository into which they discharge the detrital load borne by their waters. The sea ramifies everywhere throughout the globe, and therefore exercises an equalising influence on climate. It is the ultimate source of all streams, which, without it, have no separate existence. It must therefore rank as the greatest of all geological agents.

Composition and Volume.—A thousand parts of sea-water contain 34·40 parts of mineral matter in solution, of which common salt (sodium chloride) comprises about 78 per cent., magnesium chloride nearly 11 per cent., magnesium sulphate 4·7 per cent., sulphate of lime and potassium together 6 per cent.

Sonstadt has shown that sea-water contains over half a grain of gold per ton; and nearly all the common metals and many of the rarer have been detected in it. Oxygen, nitrogen, and carbonic acid are also present in considerable quantity, the amount of carbonic acid being estimated to be eighteen times as great as in the atmosphere.

Murray has estimated that the mean depth of the ocean is 12,456 feet, and that the total amount of sea-water is fifteen times the volume of the dry land above the sea. The mineral matter in solution would, he estimates, if precipitated cover the floor of the ocean to a depth of about 175 feet.

The total river discharge into the sea is estimated at 6524 cubic miles per year, carrying half a cubic mile of mineral matter. At this rate it would take the streams 9,000,000 years to add to the sea an amount of mineral matter equal to what it now contains, figures which contain a useful suggestion as to the age of the ocean.

WORK OF THE SEA.

The sea as a geological agent (*a*) *erodes* and *wears away* the dry land; (*b*) *sorts* and *spreads out* the material poured into it by streams and rivers, as well as the products derived from its own erosive work; and (*c*) by its currents *transports* material from one place to another. In other words, the sea is (1) *destructive* and (2) *constructive*.

THE SEA AS A DESTRUCTIVE AGENT.

Erosive Effects of the Sea.—This is (*a*) *chemical* and (*b*) *mechanical*.

Chemical Effects.—The extent of the chemical effects of the sea have not yet been investigated to any extent. It is, however, well known that solutions of salt (sodium chloride) exercise a corrosive effect on many rock-forming minerals. Besides, sea-water, as stated above, contains a considerable amount of free carbonic acid, the corrosive and disintegrating effect of which on the felspar minerals of rocks or limestones and calcareous aggregates of all kinds cannot be less than that of the atmospheric carbonic acid on the same kind of rock when forming dry land. The chemical erosion of the sea, although no more measurable to the eye than the gradual and silent waste of an undulating upland, must be considerable in the course of the centuries, and by its softening and disintegrating action cannot fail to be a powerful ally to the more active and apparent forces of mechanical erosion.

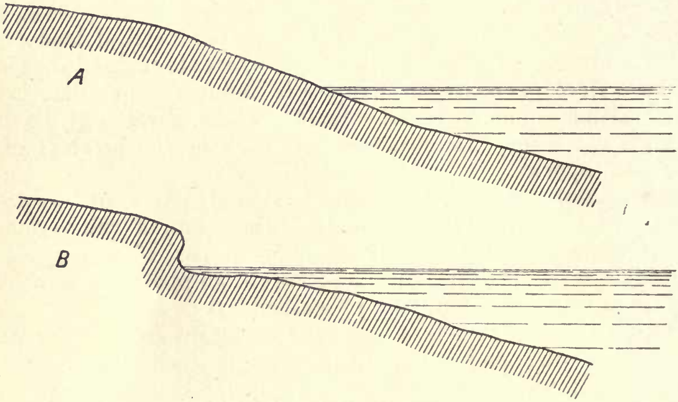

FIG. 31.—Coastal erosion.

A, Showing form of shore before erosion.
B, Showing sea-cliff after erosion.

Everyone must have observed how prone to decomposition and surface weathering are the rocks exposed in cliffs facing the sea. This may be in part due to the briny spray which is carried over the land by the wind, and in part the work of the powerful and active oxidiser ozone which is more abundant on the seashore than elsewhere.

Mechanical Effects.—The most obvious effect of the sea is seen in the cutting back of the land so as to form steep faces and cliffs.

The rate of cutting back or recession of the land will depend on the hardness of the rock, its composition, presence or absence of joints, stratification or cleavage planes. Where the rock consists of alternating hard and soft beds, the soft beds will be cut back more rapidly than the hard, thus leaving an overhanging cornice of hard rock. Even the hardest rocks possess relatively little transverse strength; consequently the overhanging ledge soon breaks off owing to the stress of its own weight.

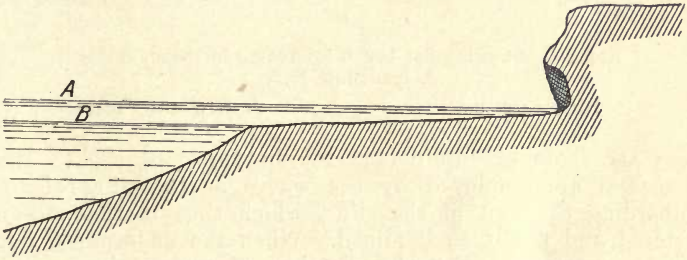

Fig. 32.—Showing marine erosion of sloping bench in Auckland Harbour, N.Z.

A, High-water mark. *B*, Low-water mark.

The masses of broken rock fall to the foot of the cliff, where they act as a protecting apron by breaking up and in part destroying the erosive effect of the advancing waves. But in time the fallen blocks become pounded up and removed, and once more the active undermining of the sea-cliffs begins.

The manner in which marine erosion is effected varies with the mood of the sea. In its normal mood, which is the tranquil or semi-tranquil, the sea by the constant rise and fall of the tide alternately covers and uncovers a marginal strip of land that in time becomes worn down into a bench that slopes from *low-water* to *high-water mark.* Where the rocks are soft, the bench may be worn into a flat platform lying a foot or two above low-water mark (fig. 33).

During, and for some time after a heavy gale, the sea flings itself furiously against the shore, and in this mood it is very destructive. Pinnacles of rock that have been undermined or loosened by the thundering blows of previous storms are toppled over, while the overhanging portions of cliffs are torn off and the debris spread along the strand, where it is slowly broken up and rounded by the unceasing wave-action of the advancing and retreating tides.

Masses of rock that in normal times lie undisturbed at the foot of the cliffs, during great storms are picked up by the advancing waves and hurled against one another with terrific force. Or where the shore is unprotected by an apron of broken rock, the masses are employed by the waves as battering-rams for bombarding the foot of the cliffs, which thus in time become shattered and finally undermined. When the undermined overhanging portion of the cliff breaks off under the force of gravity, the tumbled rock provides fresh ammunition for another bombardment.

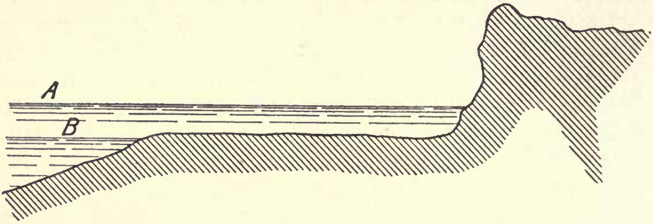

Fig. 33.—Showing flat bench excavated in chalky marls, Amuri Bluff, N.Z.

A, High-water mark. *B*, Low-water mark.

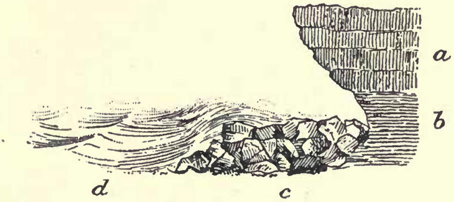

Fig. 34.—Showing coastal erosion.

Wave and Tidal Effects.—The constant movement of the sea gradually eats away the edge of the land, and, obviously, if the process were continued long enough, first the islands and then the continents would be shorn down to an almost even plain not much below sea-level. As a matter of fact, many flat reefs that are just awash at low-water are all that now remain of what were at one time islands standing near the mainland. But the power of the waves does not end here. The angular blocks that are broken off the cliffs are acted on by the tidal movements of the sea as well as by the larger waves of fierce storms, and in time become worn down and rounded. The sharp angular blocks lie along the foot of the cliffs. In the tide-way the blocks are somewhat rounded and smaller. Further out the blocks get smaller and smaller, and more and more rounded, until they eventually pass into *shingle* or beach-gravels. Still further out the shingle becomes smaller and smaller, and finally graduates into sand.

The push and drag of the tides rolls the shingle over and over, and by this everlasting attrition and grinding, the pebbles become more and more rounded, and consequently smaller and smaller, until eventually they are reduced to sand. In the same way the swish of the waves causes a similar abrasion and grinding of the sands, which in time are reduced to a fine silt which is caught up by currents and spread far and near over the floor of the sea. The place of the ground-up shingle and sand is constantly replenished by fresh material broken from the cliffs, which are continually crumbling away under the combined attack of subaerial and marine erosion.

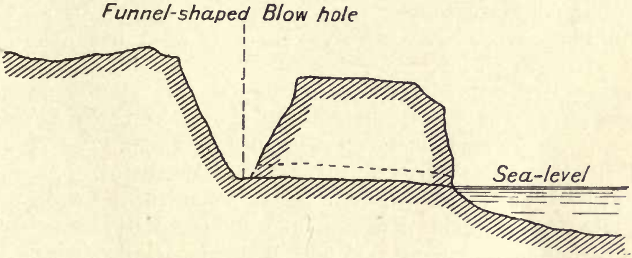

FIG. 35.—Showing funnel-shaped blow-hole, Puketeraki, N.Z.

Erosive Effect of Compressed Air.—When the advancing waves fling themselves against a fissured cliff, or one containing fissure-like cavities such as are frequently formed along joint planes or the stratification lines of inclined strata of different degrees of hardness, the contained air is compressed by a pressure equal to the force exerted by the falling wave. When the wave suddenly retreats, the air expands with shattering force, and in this way the cracks and fissures are enlarged and fresh ones opened.

In some places the fissures communicate with the upper surface of the cliff, forming what are known as *blow-holes*, from which air and spray or even a column of water may be projected with great force when the waves dash on the cliffs below. As time goes on, the blow-hole becomes larger and larger, until at last a cavern with a wide funnel-shaped opening on the top of the cliff is formed as shown in fig. 35.

Erosive Effects of Floating Ice.—In the high latitudes of both hemispheres where the seas, lakes, and rivers become frozen over in winter, the effects of ice-erosion are sometimes very striking.

In spring when the river-ice breaks up, it is frequently piled up in narrow gorges until a block takes place. When the impounded waters eventually break away, the sharp-edged sheets of ice scrape and fret against the banks, which in time become undermined and ultimately break away in long strips. Where the course of the river runs through alluvial flats the ice is particularly destructive.

When the ice breaks up in lakes, the floating masses move towards the outlet, where they sometimes accumulate until a "jam" takes place. The force exerted by ice piled up in this way is enormous. Logs of wood entangled in the "jam" are frequently broken into splinters, while all the rocks within the reach of the ice are scored and carved into ledges, or shattered and tumbled over. This erosive effect is seen in most Arctic gulfs and narrow seas.

Floating bergs moving past headlands and along contracted passages chafe and grind against the shores, whereby they may in time excavate narrow benches in the solid rock. Some of the raised benches that contour around the fiords of Norway are believed by some writers to have been formed in this way.

Topography of Marine Erosion.—In sheltered bays the shore is generally bounded by low undulating downs fringed with a strip of sandy beach. Typical examples of this are seen on the shores of the Wash, in England, and Golden Bay, in New Zealand. The headlands enclosing or sheltering such bays frequently present steep cliff-faces to the sea, the formation of which in these exposed situations is commonly the result of the more rapid erosion of the land by the prevailing sea-currents.

Where the bay is land-locked, the cliffs may extend some distance inside the harbour, their excavation being the work of the incom ingand outgoing tides which travel with great velocity in narrow passages, and are hence endowed with great erosive power (Plate XI.).

In many places where the coast-line is deeply indented with numerous ramifying bays and fiords, the land everywhere rises steeply from the water's edge. In these cases the neighbouring land is generally high and mountainous. The fiords are deep valleys that have become invaded by the sea through the submergence of the land. They are what are known as *drowned valleys*, and the steepness of their shores is mainly the work of subaerial agencies of erosion. The newer cliffs of marine erosion that

SEA-CLIFF OF TURNER GLACIER, ALASKA. (After Tarr, U.S. Geol. Survey.)

are sometimes seen in process of formation in these land-locked fiords can easily be distinguished from the old valley contours. Fine examples of this class of coastal topography are seen on the coasts of Chile, Alaska, and New Zealand, but their configuration has no relation to marine erosion.

On exposed coast-lines the shore is generally bounded by steep cliffs that may vary from a few feet to many hundreds of feet high. These cliffs may present many diversities of form according to the character of the country rocks. The hardness of the rocks, the presence of bedding and joint planes, the direction of the dip and strike of stratified rocks, all tend to retard or accelerate the progress of marine erosion. Generally speaking, the softer coherent rocks present steep cliffs with even slopes; while sandstones and all the harder rocks, such as basalt and granite, give vertical and fantastic forms that are frequently undermined, tunnelled, and arched. Where the rock is fissured or intersected by joints, narrow tunnel-like caves will be formed, along which the waves will rush with great force. Where the rock is intersected by two sets of joints, the recession of the cliffs may result in blocks or stacks of rock being left standing as outlines or pinnacle-shaped islands.

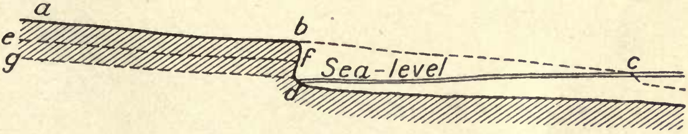

FIG. 36.—Showing effect of coastal recession on river grading, S. Canterbury, N.Z.

In all cases the softer rocks will be worn away more rapidly than the harder; therefore, while the former will be eaten back into bays and inlets, the latter will form the headlands.

Effects of Coastal Recession on River Grading.—The cutting back of the coast-line shortens the length of the streams and rivers that drain into the sea. The obvious effect of this recession and shortening is to give the rivers a greater velocity on account of the steeper gradient. The greater velocity enables a stream or river to regrade and cut down its bed.

The effects of coastal recession are always most marked where the river flows over an alluvial plain before entering the sea. The river in this situation is enabled, in the process of cutting down its bed to its base-level—the sea, to excavate terraces in the lower part of its course. The effect of coastal recession as regards terrace formation is therefore the same as an elevation of the land.

The Canterbury Plains in New Zealand are composed of gravel-drift carried down from the alpine ranges by a number of large rivers. They extend along the coast for over a hundred miles; and north of Timaru, where the coast is swept by a strong northerly current, they have been cut back until they present sea-cliffs, varying from 10 to 50 feet high, the highest cliffs being found where the recession is greatest. The old plane, along which the rivers flowed before the cutting back of the coast-line, is indicated by the line *a b c* (fig. 36), the former point of discharge being at *c*. By the wearing away of the land the point of discharge is now at *d*, and *b d* shows the height of the present sea-cliff. The present plane of flow is along *g d*. During the process of cutting down their beds, the rivers have excavated a series of terraces as indicated by the broken line *e f*. The old flood-level *a b* now forms the highest terrace.

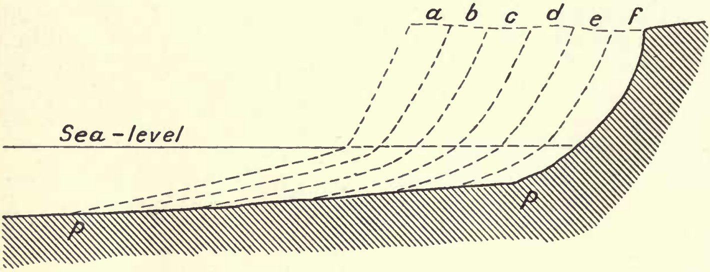

FIG. 37.—Showing formation of plain of marine denudation.
a, b, c, d, e, and *f* are successive slices shorn off the edge of the land forming the marine plain *p p*.

Plain of Marine Denudation.—In a preceding chapter we found that the general effect of all the processes of subaerial denudation was to wear down the dry land to a base-level or peneplain; and similarly we find that the final effect of all the processes of marine erosion is the slicing away of the edge of the land to a horizontal or gently sloping platform to which the name *plain of marine denudation* is applied. The existence of this marine shelf is proved by the soundings around the coast-line. It is found that nearly all the continents and larger islands are surrounded by a marine shelf.

The shelf generally slopes gently seawards, and when its edge is reached there is a sudden drop in the floor of the sea. The manner in which this marine shelf is carved out of the land will be easily understood by a reference to fig. 37.

Where the land fronting the sea is high, the shelf is generally narrow, and where low it is relatively wide. But the total amount of erosion is probably about the same everywhere, for the greater height and less width in one place will balance the less height and greater width at another.

Where the land has been recently elevated, the dissected remains of ancient plains of marine denudation can still be clearly traced in regions lying near the sea.

Rate of Marine Erosion.—The rate of marine erosion is dependent (*a*) on the resistance offered by the rocks, (*b*) on the erosive power of the waves, and (*c*) on the transporting power of oceanic currents.

Soft rock or incoherent gravel and sand will be worn away more rapidly than hard rock. Moreover, the rate of erosion will be more rapid on a bleak coast-line exposed to the force of storms sweeping over a wide expanse of sea than in sheltered bays and land-locked harbours, or on the lee-side of a cape or peninsula.

When the wind blows for some time over a broad expanse of ocean, the water is piled up against the shore, with the result that the waves are able to reach far above the point reached by normal tides. When the heaping up of the water happens to coincide with high-water, the erosion effected by the pounding of the abnormal waves may, in a few hours, exceed the normal tidal erosion of half a year or more.

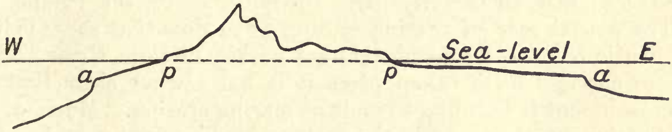

FIG. 38.—Showing section of marine shelf around Otago, N.Z., to 100-fathom line.

(*a*) Edge of marine shelf.

The cliffs excavated in compact rock are generally steep and often overhanging. Unconsolidated material, on the other hand, naturally assumes the angle of rest, and hence commonly presents gentle slopes to the sea.

A compact homogeneous rock, like granite, when unfissured frequently wears away into dome-shaped forms that have a curious resemblance to the rounded *roches moutonnées* of glacial erosion. The smooth dome-shaped islands and headlands on the coast of Western Australia, where there is no reason to suspect recent glaciation, are notable examples of this form of erosion which is the united work of subaerial and marine denudation.

When stratified rocks dip towards the sea, landslips are of frequent occurrence, as a small amount of excavation at the foot of the cliff is generally sufficient to destroy the supporting toe of the block.

The undermining and breaking up of the hard rock provides boulders and shingle, which the waves use with destructive effect in carrying on the assault on the land fringing the shore. On the other hand, soft rocks like chalk, marls, and shaly clays provide no materials for the making of shingle, except they happen to contain nodules of flint, as chalk and chalky clays frequently do.

Where the rocks consist of alternating soft and hard bands, the soft bands are worn away more rapidly than the hard. The result of this is that the hard bands are in time left unsupported, and soon crumble away under the vigorous pounding of the waves.

Coral reefs, submerged shoals, sand-pits, and outlying islands frequently protect the mainland from the direct influence of sea-currents, or the violence of storms. For example, the Great Barrier Reef of Australia, which runs parallel with the coast of Queensland for over a thousand miles, affords the most effective shelter against all easterly gales sweeping across the Pacific.

The actual rate of marine erosion is so slow that there is little authentic record of coastal changes within historic times. Even where changes have taken place it is not always clear that the encroachment is the direct result of marine erosion. Much of the encroachment of the sea in the eastern Mediterranean and on the east coast of Australia is obviously the result of general subsidence of the land. In other places where low-lying lands have become submerged in recent times, the inroad of the sea, if not the result of subsidence, may be due to *coastal sag*, resulting from the accumulation of a great thickness of detritus on the sea-floor. Coastal sag is always most conspicuous where the detritus rests on a soft sea-bottom.

The Sea as a Constructive Agent.

Effects of Sea-Currents.—The great oceanic currents do not reach the bottom, and therefore possess little or no power either to transport detritus or to erode the floor of the sea; but many coast-lines are swept by currents that hug the shore and run in one direction during the whole or greater part of the year. These littoral currents may be termed rivers of sea-water, and, like fresh-water rivers, they are important agents of transport and erosion.

The gravel, sand, and silt discharged by a stream or river into the head of a sheltered bay, inlet, or land-locked harbour is spread out on the bottom, where it gradually accumulates, until in time it fills up extensive areas which are thus reclaimed from the sea. It is in this way that the alluvial flats and deltas that are found fringing the head of so many bays and inlets have been formed.

But where the stream or river discharges its load into the open sea, the discharged detritus is picked up by the coastal currents and spread over the sea-floor, or piled up on distant strands, perhaps scores, or even hundreds, of miles from the river mouth. In this way vast quantities of detritus are daily moved from one place to another.

Only the fine silt and mud is carried in suspension. The bulk of the material in the form of sand or shingle is trailed or rolled along the sea-floor, and in consequence exercises a powerful erosive effect on all submerged reefs and ledges, on outlying islands, and projecting headlands. The travelling sands and shingle possess the same rasping and eroding effect as the moving sands and gravel on the floor and sides of a river-channel.

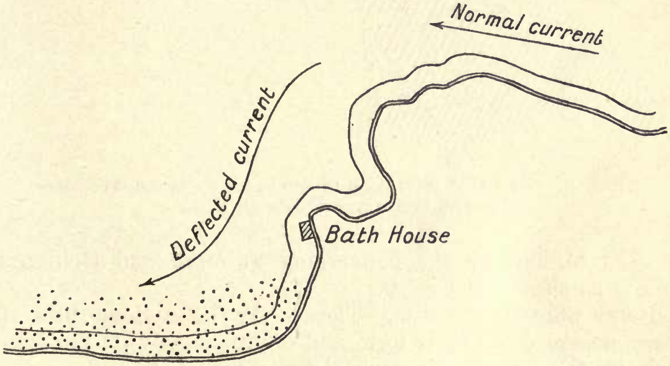

Fig. 39.—Showing piling up of sea-borne sand on sheltered side of headland at St Clair, Otago, N.Z.

Sea-borne sands generally accumulate on the sheltered side of headlands or in bays, where they form sand-banks that are sometimes awash or bare at low-water. In many places the wind piles up the sands thus placed within its reach into dunes and ridges running parallel with the beach.

The coastal currents of Otago in New Zealand travel northward all the year round. They strike Black Head at St Clair, and are diverted seawards for some distance ; but during south-east gales they are deflected inshore, with the result that many millions of tons of sea-borne sand are sometimes thrown up on the beach in the course of a few hours, frequently covering up the protecting groins as shown in fig. 39.

Where two coastal currents travelling in different but converging directions meet one another, their impact causes their rate of flow to be diminished or altogether destroyed along the line of contact, with the result that the sands they carry are allowed to settle and accumulate along that line, until submerged sand-banks and long sand-spits are formed. A notable example of this class of constructive work is found at the extreme north-east corner of the South Island of New Zealand. Here a spit of sand, 20 miles long, has been formed by the converging Farewell and Golden Bay currents as shown in fig. 40.

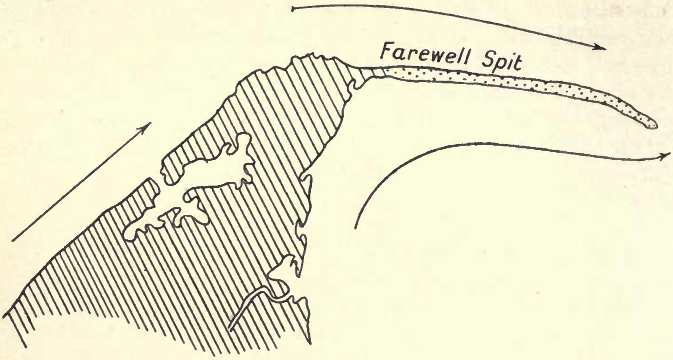

FIG. 40.—Showing formation of sand-spit by two converging sea-currents at Cape Farewell, N.Z.

Littoral Shingle Deposits.—These may be divided into three classes, according to their form and origin, namely (1) the fringing beach, (2) the shingle-spit, and (3) the shingle-flat.

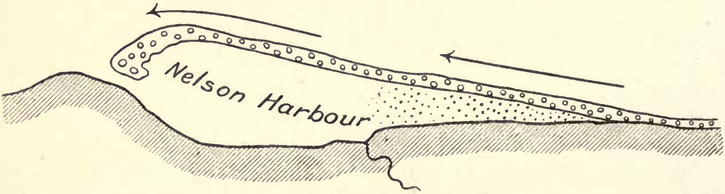

FIG. 40A.—Boulder Bank, Nelson, N.Z.

The *fringing beach* is the simplest and most common type. It consists of a strip of shingle along the strand, formed by the coastal currents directed at right angles against the shore.

The *shingle-spit* is a deposit of shingle beginning at the point where the coast-line suddenly changes its direction and turns inwards, while the current running along it still pursues its course past the point of deflection. The drifting shingle accumulates along the line of currents, and in time forms a bank or causeway that may be many miles long. The bank frequently curves inwards at its growing end. Good examples of shingle-spits are the Chesil Bank, which runs parallel with the coast of Dorsetshire for 15 miles; and the Boulder Bank, at Nelson, New Zealand, a gigantic causeway, 12 miles long, which encloses a deep, well-sheltered harbour. When the bank grows till it again touches the land it forms a *bar*.

The *shingle-flat* is formed when the coastal current, due to some local cause, follows the inward trend of the deflected coast-line, the shingle being deposited as a succession of parallel banks. In this way large areas may be reclaimed from the sea.

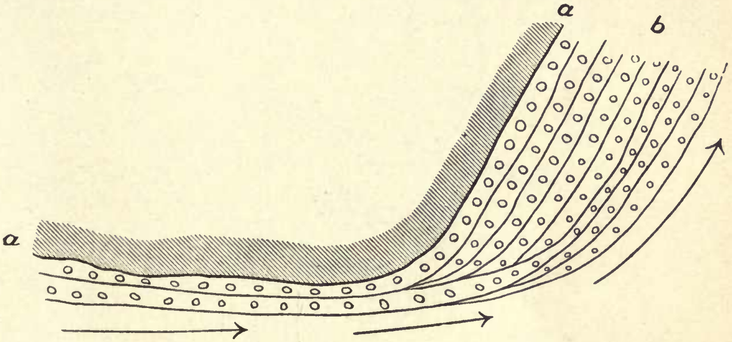

Fig. 40b.—Showing formation of marine shingle-flat.
(*a, a*) Old shore-line. (*b*) Shingle-flat.

Sorting and Spreading Action of the Sea.—The gravel, sand, and silt discharged into the sea by streams and rivers are sorted by the laving action of the waves into three main grades of different sizes. The shingle is spread along the shore in the shallow water, the sands are distributed over the sea-floor for many hundred yards on the seaward side of the shingle, while the silts and muds are transported still further seaward.

We have thus three zones of deposition running approximately parallel with one another and with the shore. There is seldom a sharp line of demarcation between the different zones. More often the one graduates insensibly into the next; but the extremes are always clearly defined. Thus the clean gravel is easily distinguished from the sand, and the sand from the silt and mud.

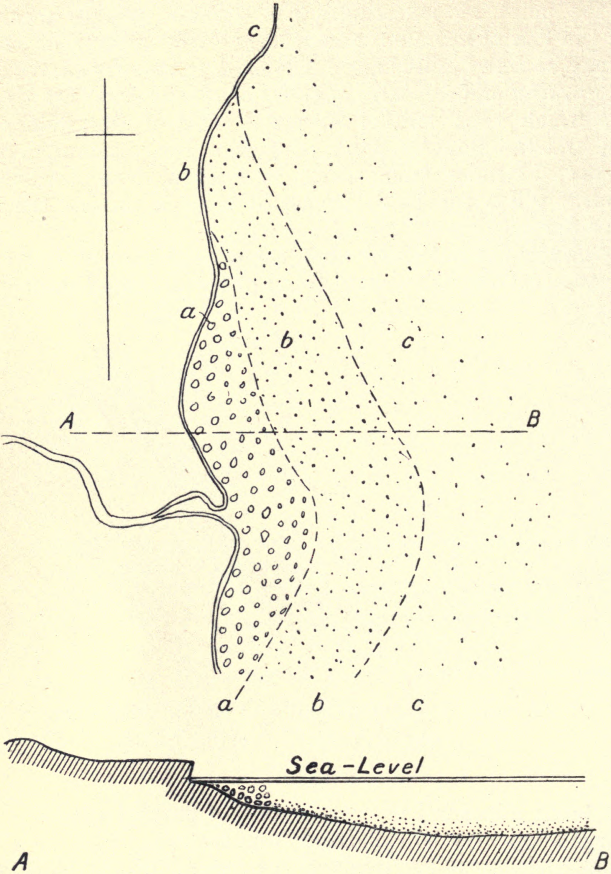

Fig. 41.—Plan showing lenticular distribution of gravel, sand, and silt on coast-line.

(*a*) Gravel. (*b*) Sand. (*c*) Silt and mud.
A B, Line of section at right angles to shore-line.

Beginning with the shore-line deposits we have thus :—

(1) The shingle and gravel zone.
(2) The sand zone.
(3) The silt and mud zone.

Where the deposition takes place without disturbance from currents, we can generally distinguish six grades of material that insensibly pass into one another, namely :—

(1) Shingle.
(2) Gravel.
(3) Sandy gravel.
(4) Coarse sand.
(5) Fine sand.
(6) Silt and mud.

Lenticular Form of Marine Deposits.—The different zones of material starting from the point of discharge are nearly always found to be more or less lenticular in form. It thus happens that in passing along the coast-line we encounter the same succession of gravel, sand, and silt as we do by following a line running at right angles to the shore-line. Thus, as shown in fig. 41, we find that the beds *a*, *b*, *c*, found along section line A B, are the same as beds *a*, *b*, *c* that successively abut against the shore-line in passing northward from the point of discharge.

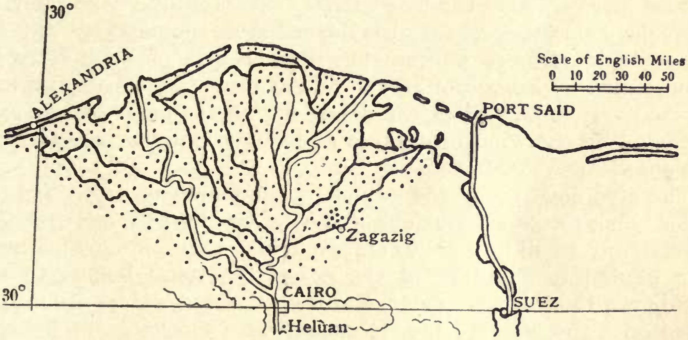

Fig. 42.—Plan showing delta of the Nile in Egypt.

Formation of Deltas.—Streams and rivers that are sluggish in their rate of flow are only able to transport sand and silt to the sea. In the absence of coastal currents the sands and silts are deposited at the mouth of the river, where they accumulate until they form obstructing banks through which the river flows in numerous intricate shallow channels. By the piling-up action of the wind at low-water, and by the deposit of sand and silt during times of flood, many of the sand-banks rise above ordinary water-level. When this happens vegetation soon establishes itself, and a *delta* is thus formed.

Estuarine Deposition.—In marine deposition, as we have seen, the coarsest material is laid down nearest the shore-line, and the finest furthest seaward; each zone of graded material being spread over a lenticular or meniscus-shaped area. In estuarine deposition this arrangement is reversed, the coarsest material being deposited at the entrance and the finest at the head of the estuary.

At the entrance the tide generally rushes in with great velocity. When once inside the harbour the tide as it advances spreads over an increasing area, with the result that its rate of flow shows a corresponding decrease.

The result of this gradual slackening of the current is that the coarsest material is deposited at the entrance, and the finest at the extreme limits reached by the tide.

In places where the coastal currents transport gravel, sand, and mud, the incoming tide deposits first gravel, then sand, and lastly mud; the first at the entrance and the last in the upper reaches of the estuary. Where the tide carries only sand and mud, as is so frequently the case, the sand is deposited at the entrance and the muds inside. Hence we find that the entrance of some estuaries is protected by a bank of gravel, and of others by shoals and bars of sand. In many cases the sands deposited inside the estuary are piled by the wind into dunes and ridges running parallel with the coast-line.

The area covered by the gravels is commonly narrow. On the other hand, the sands are deposited over a wider belt, but even this is relatively small in extent compared with the mud-covered area. The limited distribution of the coarser material is due to the rapidity with which the current of the inflowing waters diminishes when once the waters begin to spread over the banks and shoals of the estuary.

In some of the great estuaries and tidal harbours of northern and south-east Australia the mud covers hundreds of square miles, while the sands near their entrance occupy but a relatively narrow belt. In these shallow harbours the tidal waters come in laden with mud and retire laden with mud, but each tide as it slowly creeps over the mud-banks deposits a thin coating of sediment which imperceptibly but steadily raises the mud-covered area until it is high enough to enable a semi-aquatic vegetation to establish itself on its surface. In this way these tidal inlets are being gradually filled up and reclaimed from the sea.

Nearly all estuaries receive the drainage of one or more streams or rivers. Some of the larger streams discharge a load of gravel and sand into the estuary, where it is spread out and mingled with the fine harbour muds. In this way we frequently get the curious spectacle of gravels and sands mingled with almost impalpable mud, or intercalated with layers of mud.

Marine Organic Deposits.—The floor of the deeper or abysmal portions of the sea has been shown by soundings to consist of a fine calcareous ooze mainly composed of the tiny shells of *Foraminifera*, etc.

On their seaward limits, the fine mechanical sediments reaching out from the land mingle with this ooze, forming deposits which become, when hardened, what are termed *chalky clays* or *chalky marls*. The ooze itself, when free from foreign sediment, forms, when consolidated, a limestone resembling *chalk*. These organic oozes will be described more fully in the succeeding pages.

Time-Plane of Deposition.—Going seawards, the coastal gravels graduate into sands, the sands into muds, and the muds into calcareous ooze. The gravels, sands, muds, and ooze were deposited at the same time and lie on the same plane, and form what is known in geology as a *time-plane* of deposition.

Faunal Differences in Same Plane.—Each grade of material will be distinguished by the forms of life that prevailed in the zone in which it was laid down. That is, the gravels will contain the broken and rolled remains of such littoral shells as oysters, mussels, and cockles; the sands, the remains of *Pinna*, *Tellina*, and other fragile shells; the muds, minute molluscs, and foraminifera; while the ooze will consist mainly of Pteropods and various Foraminifera, among which the genus *Globigerina* will be the commonest.

A change in the character of the deposits is usually followed by a change in the fauna; but with a recurrence of the same sediments there will frequently be a reappearance of the displaced fauna; and if, in some places, the lithological character of the deposit remains unchanged, some species may persist in that place into a higher horizon than is usual elsewhere.

Besides the faunal differences due to the various character of the sediments, it is found that certain organisms inhabit shallow, and others deep water. Hence it must be remembered that faunal differences in the same plane may arise as much from *influence of station* as from differences in the texture of the sediments.

The depth of the sea normally increases with the distance from the land, but great depths may be obtained in certain conditions quite close to the land, as in the fiords of Norway and New Zealand, where a depth of 100 fathoms may frequently be found a few yards from the shore. In such situations we are liable to find a curious commingling of littoral and deep-water species.

Some organisms find a congenial habitat in muddy waters, others in clear; some flourish only on rocks and reefs, or on mud banks, exposed between the upper and lower tide-marks; and while some prefer still, clear waters, others can only exist in situations exposed to the break of the ocean-waves.

Differences of latitude, with the attendant differences of temperature, exercise a powerful influence on the character of the marine fauna. In New Zealand, which runs through 700 miles of latitude, the differences which distinguish the molluscous fauna of Southland and Cook Strait, and of Cook Strait and North Auckland, are almost startling. And perhaps no less potent than latitude is the influence of oceanic currents, as witness the widely different faunas of Labrador and Ireland arising from the Gulf Stream.

We have no reason to believe that faunal differences in the same geographical plane were relatively less conspicuous in past geological ages than they are to-day; hence, when carrying on palæontological research, we must ever remember that the most diverse faunas may be co-existent on the same geographical plane. It is this fact which often tends to render the correlation of distant formations of doubtful value.

Classification of Marine Deposits.—Marine deposits, according to their distance from the land, may, for convenience of descriptive purposes, be divided into four natural zones as under:—

(1) *Littoral*[1] *Zone*, including pebbly, sandy, and coralline deposits.
(2) *Thalassic*[2] *Zone*, including fine sediments, such as muds and silts.
(3) *Pelagic*[3] *Zone*, including calcareous accumulations that form limestones.
(4) *Abysmal*[4] *Zone*, including Red Clays of volcanic and cosmic origin.

Varying Thickness of Marine and Estuarine Deposits.—From what has been said in the preceding pages it will be obvious that all the detritus discharged into the sea, as well as the material derived from the erosion of the land by marine agencies, is sorted and spread out as a sheet on the floor of the sea. The thickness of this sheet is greatest along the shore-line, and least towards the deeper sea. Thus, if a thick bed of coastal gravel is traced seaward, it will be found to taper rapidly until it dwindles down to a thin layer that eventually emerges into the sandy zone, which in its turn thins out until it passes into silt and then mud.

The different layers of estuarine sediments are also wedge-shaped

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[1] Lat. *litus* = seashore.
[2] Gr. *thalassa* = sea, *i.e.* shallow sea.
[3] Gr. *pelagos* = sea, *i.e.* deep sea.
[4] Gr. *abussos* = bottomless.

in cross-section, being thickest at the lower end near the entrance, and least at the upper end of the estuary.

It should, however, be remembered that the distribution of both purely marine and estuarine sediments is liable to considerable variation through the disturbing influence of coastal currents in respect of the first, and of large streams or rivers in respect of the second. Disturbance from the sea-currents is, perhaps, of commoner occurrence than disturbance from large rivers, as in the case of large estuaries or mediterranean seas, the effects of the inflowing streams will be mainly local, or confined to narrow limits on the margin of the greater sheet of fine sediments. *Wash-outs* that take place during abnormal floods are often filled in with coarse, gravelly sands, or, at any rate, with material differing from that deposited in normal conditions.

The Sea as a Source of Life.—It is almost certain that the first forms of plant and animal life were aquatic or marine ; and it was probably in the sea that the first steps in the evolution of the more highly organised forms took place. The sea, ever since the beginning of geological time, has been the universal cradle and preserver of life. Earthquakes and volcanic eruptions might devastate the dry land, but in the sea, life always found a safe asylum.

Around the shores of islands and continents in the comparatively shallow water, the sea is very prolific in molluscous life. The molluscs manufacture their shells from carbonate of lime secreted from the sea-water, and where they grow in colonies, their shells frequently accumulate until they form shell-banks of great extent. Many shelly limestones that now form hard rocks are composed of shells that grew on shell-banks on the floor of the sea.

The coral polyp in the warmer seas of the tropics builds up reefs of coral that in time become converted into solid limestones.

The Sea as a Highway.—The sea stretches over the whole globe and therefore affords an easy means of migration for all kinds of marine life. The sea-currents also carry seeds and seed-spores from place to place, and thus enables vegetation to spread to new islands or to islands that have been devastated by volcanic eruptions. The comparative rapidity with which sea-borne plants may reclothe an isolated land is well illustrated at Krakatoa. In 1883 that island was overwhelmed with volcanic ejecta which destroyed all the plant and animal life. In less than twenty years the island was reclothed with a dense jungle from seeds carried to its shores by sea-currents. What we now see taking place in the dispersion of plants doubtless took place through all the past geological ages.

Fossils.—Sediments laid down on the floor of the open sea contain the imbedded remains of marine plants and shells, the bones and teeth of fishes and other creatures that lived in the sea. From a study of these fossil remains we are able to construct a picture of the depth of the sea and climatic conditions prevailing at the time the sediments were laid down.

Sediments laid down in estuaries, tidal harbours, and deltas are found to contain the bones and teeth of land animals whose bodies were washed into the sea, the shells of land and freshwater molluscs, the trunks of trees, as well as seeds, nuts, twigs, and leaves. With these are mingled the remains of animal life that frequent the brackish waters of deltas and estuaries, together with those of marine organisms washed up by sea-currents and tides.

The mingling of land, fresh water, brackish water, and marine forms is characteristic of deposits that were laid down in estuaries and mediterranean seas.

Variations of Sea-Level.—Up till the beginning of this century it was the general belief that the level of the sea was invariable, and any departure from this view was looked upon as a geological heresy. All transgressions of the sea on the dry land were regarded as an evidence of actual subsidence of the land ; and all recessions of the sea as proofs of uplift. Uplift and subsidence of the land have taken place in all geological ages, both local and continental, of small amount and of great magnitude, as the result of crustal folding or of volcanic or earthquake disturbance. It is obvious that no movement of the crust, whether it affects the sea-floor or dry land, can take place without a corresponding displacement of the sea-level. When a portion of the ocean-floor sinks, the sea recedes from the dry land, and the effect is the same as an actual uplift of the land. Conversely, when a segment of the ocean-floor rises, the sea-level is correspondingly raised, and we get a transgression of the sea producing an effect similar to an actual sinking of the land.

But the sea covers such a large portion of the surface of the globe that any changes of its level produced by the rising or sinking of crustal segments must be relatively small compared with the local effects. If the continent of Australia, due to crustal collapse, were to sink 500 feet, a large portion of its surface would be invaded by the sea, but the displacement caused by the submergence would raise the general sea-level datum less than 10 feet. Obviously the great transgressions of the sea recorded in geological history were the result of land movement rather than changes of sea-level.

DEPOSITION DURING UPLIFT AND SUBSIDENCE.

The sediments laid down on the floor of the sea and in great estuaries are the materials of which sedimentary rocks are formed.

When, therefore, we are able by actual observation to see how such deposits are laid down at the present day, we are confronted with fewer difficulties in our study of the rocks formed under similar conditions in past geological ages. In other words, the better we understand the first principles governing the deposition of sediments in lake, estuary, and sea, the better will we be able to grapple with the problems presented by the varying texture, distribution, and fossil contents of sedimentary rocks. The present conditions afford the key to the past; hence we must study present conditions in order to understand the past.

Effect of Deposition on Rising Sea-Floor.—When a general uplift of the land takes place, the shore-line advances on the sea, with the result that the sediments are, as previously described, carried further and further seaward, thereby causing *seaward overlap* whereby gravels may be deposited on sand, sand on mud, and mud on the abysmal calcareous ooze.

If the uplift is rapid and persists for a considerable time, the overlap will be more and more marked, and thus it may happen that pebble and sand beds may be eventually deposited over the calcareous ooze, the abysmal zone being now a shallow sea.

But to return to the first case where the first effect of the uplift is just sufficient to permit the sands to overlap and spread over the mud. It may happen that the uplift is followed by subsidence. In this case the shore-line will advance on the land, and the overlap will be landward, thereby permitting mud to be laid down on the newly-formed sands.

The succession of sediments in the deeper zone of deposition will now be mud, sand, mud.

If the land is oscillating with approximate regularity, we shall get many alternating layers of sand and mud. And since the deposition of mud is relatively slower than that of sand, the layers of sand will be thicker than those of mud.

Geographical Effect of Uplift.—If the upward movement continues, the partially land-surrounded portions of the sea will be at first converted into *mediterranean* seas, and eventually into land-locked lakes. If this takes place in an arid region, the evaporation of the water will leave a deposit of salt on the floor of the dried-up basin. When the infilling of the lake-basin takes place, as the result of physical and climatic changes, the deposit of salt will be covered with layers of sediment that will protect it from destruction. It was doubtless in this way that the valuable deposits of salt in England and Continental Europe were formed.

Simultaneous Deposition and Erosion during Uplift.—When uplift takes place the sediments first laid down around the shore are raised into a position where they become subject to subaerial and marine denudation; and being for the most part loose and incoherent, they are easily broken up and removed. But the mere uplift of the land does not stay the activity of the processes of denudation that were in operation before the uplift began. On the contrary, the rate of denudation may be accelerated, as the obvious effect of the uplift will be to increase the gradient of the slopes, whereby the erosive power of the streams and rivers will be correspondingly increased.

So long as the uplift continues, the ordinary products of denudation *plus* the material derived from the breaking up and re-sorting of the coastal sediments, which are now subject to denudation as the result of the uplift, are carried further seaward and spread out as a sheet that overlaps, but lies parallel with the sediments laid down before the uplift began.

Thus we see that while uplift may enable the edges of the first and consequently oldest layers of sediment to be worn away and re-sorted, deposition will still be in progress in the seaward direction. Moreover, there will be no physical break in the continuity of the layers which will follow one another in a *conformable* sequence or succession. That is, the layers will all lie in the same plane, like the slates or wooden shingles on the roof of a house.

Deposition during Subsidence.—During subsidence the sea advances on the land, and the overlap of the sediments is *landward.* In the process of time the subsidence of the land permits coastal valleys to be submerged and estuaries to be formed. It is almost certain that the piles of sediment that constitute the great geological systems were formed during downward movement.

The Cycle of Deposition.—The typical succession of sediments of many geological systems begins as a basal conglomerate and closes with a limestone, the complete sequence being (*a*) basal conglomerate, followed by (*b*) marine sandstones, (*c*) clays, and (*d*) limestone in ascending order. This succession is obviously the result of deposition on a sinking sea-floor.

The torrent-formed gravels composing the basal conglomerate were probably shot out along the foot of mountain-land fronting the sea. On a stationary or slowly rising sea-floor the gravels would be carried further and further until they eventually reclaimed a maritime belt of land from the sea. This belt would be flat, swampy, and probably deltaic.

At this stage a general subsidence set in; and as the downward movement continued, the sea encroached further and further on the land. The terrestrial gravels thereby in time became covered with marine sands, the sands with muds, and the muds with a layer of calcareous organisms that, when consolidated, formed the closing limestone member of the series.

Seams of coal are frequently found associated with the basal conglomerate, from which it may be deduced that, during the deltaic period, vegetation established itself on the mud-flats, and grew so rank and rapidly that sufficient vegetable matter accumulated to form, when consolidated, valuable seams of coal.

Each seam of coal marks an old land surface, and when we find that the different seams are separated by beds of sandstone or conglomerate, we are able to conclude that the land was slowly oscillating during the deltaic period; that is, before the general subsidence began that led to the terrestrial gravels and their seams of coal being buried beneath the succession of marine beds.

The effect of progressive subsidence is to reduce the height of the dry land; while the continuous denudation tends to reduce its surface to contours of low relief. Should the subsidence continue, the land will eventually become submerged. While the subsidence continued, the sediments spread out on the sea-floor overlapped more and more. Where there was total submergence of the land we may even find a calcareous zone or limestone riding hard on the basement rock as the result of profound overlap.

Pelagic Organic Deposits.

We have seen that, as we leave the land, the materials spread out on the sea-floor become progressively finer and finer in grain, until a limit is reached beyond which the sea is quite clear and free from sediment derived from the land.

Pteropod Ooze.—The deep-sea dredging carried out by the *Challenger* Expedition showed that, from the outer edge of the mud zone down to a depth of about 1500 fathoms, the sea-floor is covered with a calcareous ooze consisting mainly of the shells of *Pteropods* and *Foraminifera*, the former very small molluscs, the latter minute protozoans that live in beautiful chambered shells full of small pores; hence the origin of the name. In this zone the Pteropods predominate.

Globigerina Ooze.—From about 1500 fathoms down to 3000 fathoms, the sea-floor is covered with a calcareous ooze consisting almost entirely of the shells of Foraminifera, the commonest of which is *Globigerina*, from which this ooze is named.

Red Clay.—At greater depths than 3000 fathoms the calcareous oozes are absent, their place being taken by an excessively fine deposit called *red clay*. In certain areas in these abyssal depths there are deposits of *Diatoms* and *Radiolaria*, both of which are siliceous organisms, the former tiny plants, the latter minute protozoans.

The *red clay* would appear to be the very fine dust that has fallen on the surface of the sea. It consists partly of fine volcanic dust, and partly of wind-borne desert dust, mixed with what is believed to be the dust of meteors that have been broken up on entering our atmosphere.

This dust, from whatever source it is derived, must be very small in quantity, and when spread over the many millions of square miles of the sea-floor, must take thousands of years to form a layer even an inch thick.

The surface of the *red clay* is thickly scattered with the teeth of sharks, hundreds of which have been skimmed up by the dredge and brought to the surface. These teeth are so numerous that it must have taken probably thousands of years for them to accumulate, and yet the *red clay* has not been able to cover them, so slow is the rate at which it is being deposited.

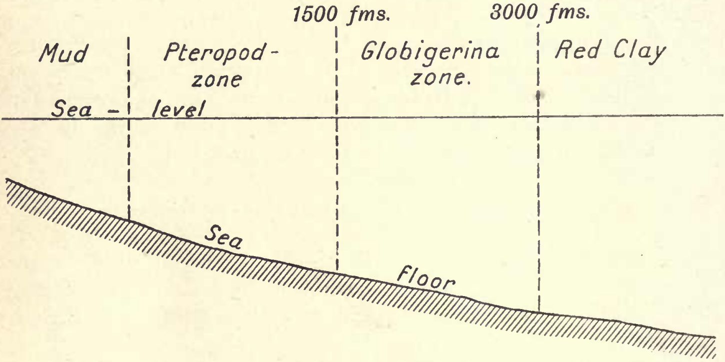

Fig. 43.—Showing zones of calcareous ooze and *red clay* in the abyssal depths of the sea.

Cause of Zonal Arrangement of Calcareous Organisms.—Both the *Pteropods* and *Foraminifera* are organisms that swim about freely at the surface of the sea. They exist everywhere in countless millions, and there is a continual rain of their dead shells which slowly fall through the water.

The empty calcareous shells of both the Pteropods and Foraminifera are soluble in sea-water; and where the depth of the ocean exceeds 3000 fathoms both are dissolved before they reach the sea-floor. Hence the absence of these organisms in the *red-clay* zone.

Pteropods are absent from the *Globigerina* zone because their shells are more soluble than those of the Foraminifera. Therefore, although the dead shells of both Pteropods and Foraminifera begin their long downward journey together, when a depth of 1500 fathoms is reached, the Foraminifera are left to continue the journey alone, the shells of the Pteropods having passed into solution in the sea-water.

Pteropods and Foraminifera are abundant near the shore in all classes of sediment, but they are not easily seen except when samples of the mud and sand are carefully washed.

The calcareous ooze of the deep sea is the material of which the chalks and limestones of some future time will be formed.

Radiolarian Ooze.—This ooze, which also contains numerous *Diatoms*, is not found so widely spread as the *red clay*, which covers the greater portion of the sea-floor below the 3000-fathom line. At the greatest depths known in the Pacific Ocean the *red clay* contains deposits of Radiolarian ooze. The Radiolaria as well as the Diatoms live at the surface of the water, but as they are composed of silica, which is but feebly soluble in sea-water, they are able to reach the bottom even at the greatest depths.

Coral Reefs.—In many tropical countries where the shores are bathed by warm sea-currents, colonies of coral of many different genera and species by their continuous growth form rock masses that are frequently of vast extent.

The conditions required for the existence of vigorous coral growth are (*a*) a mean temperature not less than 68° Fahr.; (*b*) absence of fresh or muddy water; and (*c*) warm equatorial sea-currents to provide a continuous and ample supply of food for the coral-builders.

The reef-building corals cannot live at depths below 15 or 20 fathoms, and appear to thrive best at a depth of about 7 fathoms. They are destroyed by exposure to the sun or air, even for a very brief time, and consequently cannot grow above the lowest tide-mark.

Coral reefs of great extent are found on the east coast of Australia, in the South Pacific Islands, Central America, and east coast of Africa. In the Indian and South Pacific Oceans, hundreds of the islands are entirely composed of coral rock.

Many of the great limestone deposits found in various parts of the globe, associated with the older geological sedimentary formations, were doubtless formed by coral-growth, although the proof of this is not always obtainable, as the original organic structure has been entirely obliterated by the internal crystallisation.

Coral reefs that have been recently elevated, as well as reefs submerged by the subsidence of the sea-floor, as shown by the borings carried out at Funafuti, gradually loose their organic structure. They acquire a crystalline structure like an ancient limestone, owing to the infiltration of water through their mass. The water contains dissolved carbonate of lime, which it deposits throughout the pores and crevices of the mass in a crystalline form. In this way the reef is consolidated and converted into a compact, more or less homogeneous, crystalline limestone.

During the terrific storms that at certain seasons of the year sweep over the tropical seas, the waves break off large blocks of coral which pound one another into coralline sand and mud, or are hurled with destructive effect against the living coral reef, from which fresh blocks are thereby torn. After a storm the shores of a coral island are frequently piled up with sand and fragments of coral—the wreckage of the submerged reefs. At the height of the storm, and even for some hours after it has abated, the sea is discoloured with coral-mud for a distance of several miles beyond the outer reef. The detritus that is not heaped up on the beaches is spread as a sheet on the sea-floor, where it is in time consolidated by infiltration, forming a foundation for the renewed growth of the coral-builders.

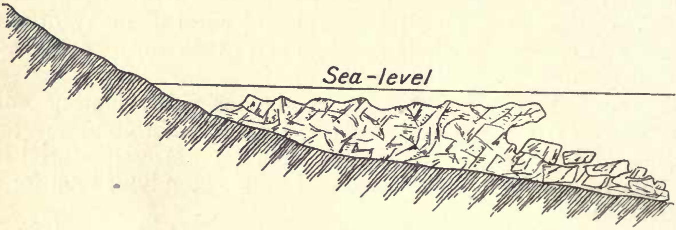

FIG. 44.—Showing growth of coral reef on stationary or slowly rising sea-floor.

Formation of Coral Reefs.

Coral reefs may grow (*a*) on a stationary or slowly rising sea-floor, or (*b*) on a sinking sea-floor. When they grow on a stationary or slowly rising floor they extend outward, forming tabular masses, while on a sinking shore-line they grow upward.

Growth of Coral Reefs on Stationary or Slowly Rising Floor.—The living coral grows vigorously only on the outside or *seaward* side of the reef. That is to say, it grows towards the source of the food-supply. In this outward growth, being unable to live below the 20-fathom line, it spreads outward, forming huge mushroom-shaped masses. In time the overhanging cornices break off in large slices, partly owing to the stress of their own weight, and partly owing to the force of the waves during storms. The broken masses fall to the sea-floor. In this way, by the continuous growth and breaking up of the reef, the blocks, mingled with sand and mud, accumulate until they rise to the 20-fathom line, where they form a new foundation for the ever active myriads of coral polyp.

On a stationary sea-floor the coral reef thereby gradually spreads seaward, forming a tabular sheet of increasing thickness.

When the sea-floor is slowly rising, the outward growth is relatively rapid; hence the calcareous sheet is more uniform in thickness.

In Fiji and other Pacific islands, consolidated tabular sheets of uplifted coral reef can be traced inland for many miles, their crystalline structure resembling that of many of the ancient sheets of limestone, intercalated with the Wenlock, Carboniferous, and Jurassic formations.

Growth of Coral Reef on Sinking Sea-Floor.—If the land is sinking at a less rate than the growth of the reef-building, the corals will be able to maintain their place above the 20-fathom line, and hence will grow *upward* and *outward*. If the water outside the reef is deep, the outward growth will be relatively slower than the upward. If the rate of subsidence competes with the growth of the coral, the builders will just be able to maintain their position, and the floor of the sea will be covered with a sheet of coral reef, the extent of which will depend on the duration and amount of the subsidence.

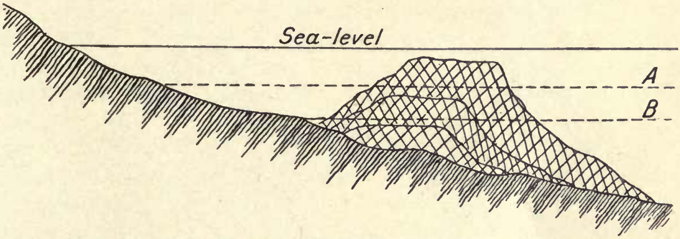

Fig. 45.—Showing formation of Barrier Reef.
A and B are old shore-lines.

Formation of Barrier Reefs and Atolls.—These are believed to have been formed by the upward growth of coral on a slowly sinking shore-line. This view was first advanced by Darwin, and is now generally accepted by geologists; but the theory of *outward growth* advocated by Murray has many supporters.

When the coral reef is marginal to a sinking continent or large land-area, a *barrier* reef is formed. For, as the sea-floor continues to sink, the coral reef grows upward, the shore-line at the same time receding further and further from the reef. The water between the reef and the shore thus becomes deeper and deeper as the subsidence progresses until a *barrier* reef is formed, as shown in fig. 45.

When the coral reef grows around the shores of an island, the united result of the upward growth of coral and progressive sinking of the land is to form a fringing reef marginal to the old shore. When the subsidence continues until the island is completely submerged, all that remains to mark the former existence of the island is a ragged ring of coral reef, forming what is called an *atoll.*

The wreckage of the reef, piled up by the waves and wind, in the course of time raises the reef above sea-level; and, as the land continues to sink, the inside lagoon becomes deeper and deeper.

The theory of outward growth and dissolution, as advocated by Murray, assumes that atolls were built up on marine banks or platforms, on which the coral polyps established themselves and formed a sheet that in time grew to the surface. At this stage the growth would be on the outside fringe of the reef, exposed to the break of the ocean waves, from which the polyps derived their food-supply; and here, by the action of the waves, the rim of the reef would in time rise above the surface. The corals on the inside portion of the sheet, being deprived of their food-supply, would soon decay and dissolve, thereby forming a lagoon. As the growth would be outward, the reef would gradually extend seaward, the living polyps building on the apron of broken coral on the outer slope of the reef. At the same time, the lagoon would become larger and larger by the continual dissolution of the dead coral inside the living barrier.

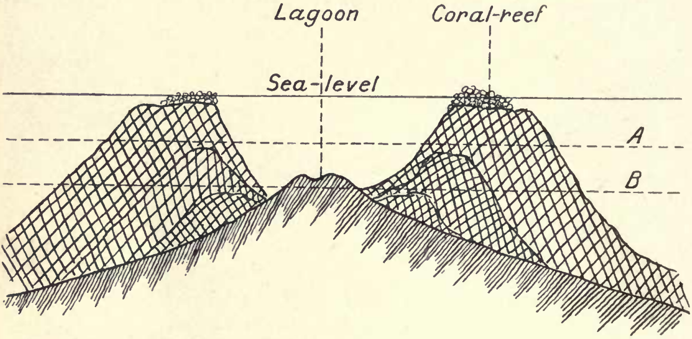

FIG. 46.—Showing progressive stages and formation of fringing reef or *atoll.* B and A, former level of sea.

Agassiz pointed out the frequent occurrences of uplifted coralline limestones, which might be worn down and dissolved, while fringing reefs grew around them, thus producing barrier reefs and atolls in association with elevation instead of subsidence.

According to the view formulated by Darwin, the Pacific Ocean, with its hundreds of atolls, must be regarded as an area of subsidence, the existing islands marking the site of the higher peaks and ridges of a submerged continent. It we assume the truth of this, we are at once faced with the question, Why did the coral polyps refrain from building till the peaks and summits of the mountains were just on the point of complete submergence? If the subsidence view be true, then the original limits of this ancient continent ought to be outlined by the barrier reefs that girdled the receding and deeply embayed sinking land, like the great barrier reefs of Australia and New Caledonia. But of such mighty barriers we can find no trace.

Subsidence and upward growth seem to afford a satisfactory explanation of the production of barrier reefs; and if accepted as satisfactory for atolls, we must assume that the rate of subsidence of the ancient continent postulated above was too rapid to permit the upward growth of coral reefs on the site of the sinking strands till all but the higher points of the land were submerged.

Distribution of Coral Reefs and Islands.—The great Barrier Reef on the north-east coast of Australia is 1250 miles long, and varies from 10 to 90 miles wide. It is usually about 20 miles from the shore, but in places the distance increases to 50 or even 90 miles. The depth of the channel varies from 50 or 60 feet to as much as 60 fathoms in the southern part, where the reef lies furthest from the mainland.

The barrier reef of New Caledonia is 400 miles long, and the average distance from the land is about 10 miles. The length of New Caledonia is 250 miles; so that we may conclude that subsidence has shortened the island by a distance of 150 miles since the coral reef began to grow on its shore.

Over 200 atolls, or true coral islands, the majority of them only a few feet above sea-level, are scattered throughout the Indian and South Pacific Oceans. The principal atolls in the Indian Ocean are the Laccadive and Maldive Islands, the Chagos Bank, and the Saya de Malha, which form a stretch of submerged land between India and the north of Madagascar. It is not inconceivable that such a group of islands, before they were submerged, may have formed a continuous land connection from Mozambique to the Malabar coast of India. Such a connection would help us to understand the presence of an African element in the Indian land fauna.

In the South Pacific the principal atolls are the Low Archipelago, Gilbert Group, Marshall, and Caroline Islands.

The ring of coral reef forming an atoll is generally breached in one or many places, thereby giving access to the lagoon inside.

Coral reefs of great extent exist on both shores of the Red Sea. They extend down the Zanzibar coast and the coast of Mozambique, and surround the Mauritius. If subsidence of the east coast of Africa were to take place, the former would form barrier reefs running parallel with the present coast-line.

Lacustrine Limestones.—The limestones formed on the sea-floor have their correlatives in lakes. Some lacustrine limestones are composed of freshwater shells, or the calcareous secretions of freshwater algæ that flourished in the clear water. Others were formed by precipitation from solution. Many of these calcareous deposits have been consolidated by the dissolution of bicarbonate and the re-deposition of carbonate of lime, but some of those of late Tertiary date are still loose and pulverulent.

SUMMARY.

The Sea as a Destructive Agent.

(1) The erosive work of the sea is *chemical* and *mechanical.*

(2) The free carbonic acid contained in sea-water converts limestones into the soluble bicarbonate of lime; dissolves the binding medium in all kinds of calcareous rocks; and attacks the felspar of igneous rocks, such as granite and basalt. Limestones are thus slowly worn away, while calcareous and igneous rocks are first disintegrated and then destroyed.

The free oxygen in the sea-water continues the disintegration effected by the carbonic acid by oxidising the iron in the iron-bearing minerals.

(3) The greatest erosive effect of the sea is the work of the tides, sea-currents, and waves set in motion during storms. In this way the edge of the land is gradually eaten away, the softer rocks being shorn back, while the harder are undermined until they finally become shattered and broken up. The blocks of hard rock accumulate at the foot of the cliffs, where they at first form a protecting apron, but are afterwards broken up and rounded, in time forming shingle, and finally sand and silt. During great storms blocks of hard rock are flung with destructive effect against the cliffs.

(4) Soft rocks are worn away more rapidly than hard; thus in time the former are worn back until they form bays and gulfs, while the hard rocks remain as steep cliffs and projecting headlands.

(5) In high latitudes masses of floating ice abrade the rocks, and may even wear away the edge of the land into benches.

(6) The recession of a coast-line shortens the course of streams and rivers, which are thus enabled to regrade and cut down their beds. In this way rivers, in the process of cutting down their beds, may excavate terraces in the lower portion of their course, the effect of recession being the same as an elevation of the land.

(7) The total effect of all the processes of marine denudation is the cutting away of the land to an even platform called a *plain of marine denudation.* Nearly all large islands and continents rise from a marine shelf or platform of this kind, as shown by soundings around their shores.

The Sea as a Constructive Agent.

(8) The sea is the final destination of nearly all the products of denudation of the dry land. Streams and rivers continually discharge an enormous load of gravel, sand, and silt into the sea, where it is sorted and spread out, the coarser material near the shore, the sands in deeper water, and the silts and muds still further seaward. Many harbours and bays in time become filled with detritus, and in favourable situations sand-banks and shoals of sand may be formed far out from the land. Converging sea-currents may form sand-spits of great length.

(9) In estuarine deposits the coarsest are laid down near the entrance, and the finest at the utmost limits reached by the flowing tide. Where streams discharge coarse material into the estuary, these are mingled with fine harbour muds.

(10) The sea is the cradle and preserver of life. By its great extent it affords unrivalled means for the migration and dispersion of land plants, and all kinds of marine life.

(11) The remains of plants and animals are embedded in deposits of all kinds—marine, estuarine, fluviatile, lacustrine, and volcanic—and there preserved from destruction. They form valuable records of the contemporary life, climate, and physical geography of the period of deposition.

(12) When deposition takes place during uplift of the land the marine sediments are carried further and further seaward, whereby *seaward overlap* takes place.

(13) The geographical effect of continued uplift is to convert partially land-surrounded portions of the sea into seas of the *mediterranean* type, and eventually into land-locked basins or lakes, in which, by evaporation, deposits of salt may be laid down.

(14) During uplift, deposition of sediments continues without cessation, the sediments being merely carried further and further outward or seaward. But while this is taking place, the upward movement of the land has raised the old shore-line above sea-level, with the result that the coastal edges of the sediments first laid down are subject to the wear and tear of subaerial and marine agencies of denudation. The shoreward portions of these older layers are thereby broken up, re-sorted, and spread out on the sea-floor along with the ordinary products of denudation of the land.

Thus we see how it is that deposition and erosion can proceed at the same time during uplift of the sea-floor.

(15) During subsidence the sea encroaches on the land, and the sediments overlap one another in a *landward* direction. It is probable that all the piles of sediments forming the great geological systems were laid down during downward movement of the land.

(16) In a typical cycle of deposition we find that gravels, sands, and muds shot down on a stationary or slowly rising sea-floor in time reclaim a maritime belt from the sea, producing conditions that are frequently deltaic. When a progressive subsidence takes place, these terrestrial deposits are covered over with marine sands, followed by marine muds. These may be followed by a layer of calcareous organisms that, when consolidated, will form a bed of limestone which will close the cycle of deposition. In other words, the cycle begins with terrestrial sediments, and ends with a deep-sea deposit, provided the subsidence is continued.

During the deltaic period, if the climatic conditions are favourable, rank vegetation may establish itself on the level swampy coastal lands, and if it remains long enough, sufficient decaying vegetable matter may accumulate to form valuable seams of coal. When the general downward movement begins, this vegetable matter will be covered over with sands and other sediments, and thereby protected from destruction.

The presence of two or more seams of coal would indicate that the land was slowly oscillating during the deltaic period—that is, before the general downward movement was fairly started.

(17) The abysmal deposits of the sea consist of various calcareous oozes that below the 3000-fathom line give place to the *red clay*, composed of volcanic, desert, and meteoric dust that settled on the surface of the sea.

(18) The continuous growth of coral in warm tropical seas forms large masses of calcareous rock, which, by the infiltration of calcareous waters, assume a crystalline structure resembling the older Palæozoic limestones.

(19) On a stationary or slowly rising sea-floor the coral reef grows *outward*, forming tabular masses. On a sinking sea-floor the growth is mainly *upward*.

(20) Coral reefs growing on the shores of a sinking continent or large land area form *barrier reefs* ; while those that grow around a sinking island form *fringing reefs*. When the island inside the reef finally disappears below the surface of the sea, an *atoll* or true coral island is formed.

(21) Marine limestone have their correlatives formed in fresh-water lakes.

CHAPTER VII.

ROCK-BUILDING.

THE CONSTRUCTION OF SEDIMENTARY ROCKS.

BY far the greatest visible portion of the Earth's crust is composed of sedimentary or aqueous rocks. We will therefore now consider the original constitution of these rocks as resulting from the conditions under which they were formed.

Among the various structures to be considered are *stratification*, *false-bedding*, and *lamination*.

Forms of Bedding.

All fragmentary material derived from the denudation of the land is eventually laid down on the bed of the sea or on the floor of some lake or river, where it is sorted by the action of the water and spread out in layers or beds which are also termed *strata*.[1]

The strata or beds, according to the conditions in which they were formed, may be *marine*, *lacustrine*, or *fluviatile*. In other words, the layers of gravels, sand, and mud laid down on the floor of the sea form what are termed *marine* beds; those deposited in a lake-basin, *lacustrine* beds; and the deposits laid down in a river-bed, *fluviatile* beds.

Stratification.—We found in the last chapter that the detritus discharged into the sea is *sorted* and *spread out* into three principal zones running nearly parallel with the shore, the coarsest material being deposited nearest the shore, and the finest furthest seaward.

The material in each zone is approximately uniform in size, the sorting or grading into sizes resulting from the operation of the well-known hydraulic principle that *equal particles falling in water offer an equal resistance.* This principle can easily be illustrated by throwing a mixture of coarse sand, fine sand, and silt into a tall glass jar filled with water. The coarse sand, fine sand, and silt will after a little time be found to have settled in three distinct layers, the coarsest being at the bottom because it fell the

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[1] *Strata*, the plural of *stratum* = a layer or bed.

quickest, with the finest at the top because it settled the slowest (fig. 47).

The deeper the water into which the mixture is thrown, the more complete will be the separation, and the cleaner the products in each layer.

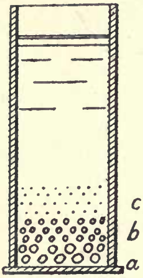


FIG. 47.—Showing sorting action of still water.

(*a*) Coarse sand. (*b*) Fine sand. (*c*) Silt.

The separation or sorting just described takes place in still water, a condition which is seldom or never met with in nature.

Let us now assume that a similar mixture is thrown into the head of a long box-launder or chute through which there is flowing a slow stream of clean water. The flowing water possesses the same sorting action as still water, and we shall again obtain three sorted products; but instead of these being arranged vertically one above another as in our first experiment, they will be spread out in the same plane, the falling particles being deflected in their descent in the direction of the flowing water.

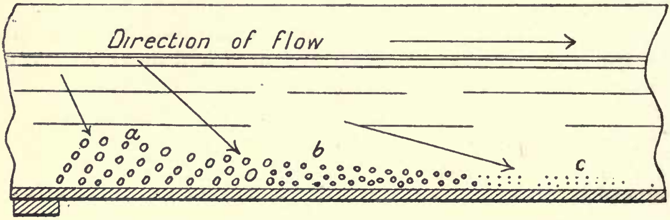


FIG. 48.—Showing sorting and spreading action of moving water.

(*a*) Coarse sand. (*b*) Fine sand. (*c*) Silt.

The particles have two motions—a vertical and a horizontal; hence, the more slowly they fall through the water, the greater will be the travel or deflection before they settle on the bottom. And since the heaviest particles fall first and the finest the last, we shall get the coarse sand at the head of the launder, the fine sand in the middle, and the silt at the tail, as shown in fig. 48.

Thus, for the *sorting* and *spreading out* of detrital material we require the water to be in motion, and of course this condition is always provided in the case of the sea by the daily tides, sea-currents, and the wave motion generated by winds.

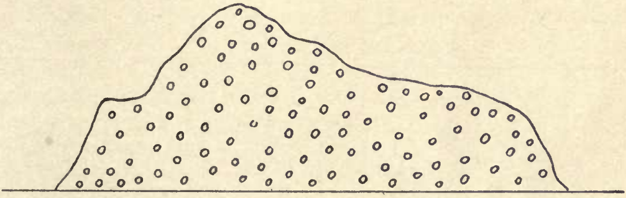


FIG. 49.—Showing conglomerates without bedding.

The gravel and shingle lying near the shore-line form conglomerates; the sands spread further seaward, sandstones; and the muds, still further out, form mudstones and shales.

Conglomerates frequently exhibit no stratification or lines of bedding, and when they do, it is generally caused by the occurrence in them of layers of finer or coarser material. Thus, bands of sandstone or shale impart a bedded appearance to the layers of conglomerate lying between them.

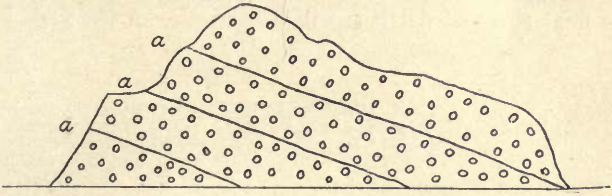


FIG. 50.—Showing conglomerates with bands of sandstone, *a–a*, imparting a bedded appearance.

Fig. 49 shows a section of a bluff of conglomerate which exhibits no appearance of bedding; but the same conglomerate when it contains sandstone bands *a-a*, is seen to present a bedded or stratified appearance.

It should be noted that the bands of sandstone that occur in a conglomerate are generally extremely variable in thickness and linear extent. This is what might be looked for where fine material is laid down among coarse, the fine being in most cases deposited during a temporary inset of the coastal sea-currents by a continuance of heavy weather or seasonal causes.

The floor of the sea around the coast-line is not level, but, on the contrary, full of hollows, ridges, and minor inequalities, resulting from the unequal resistance of the rocks to the wear and tear of the sea.

The first detritus laid down on the floor of the sea will be spread out as a sheet which will be of variable thickness. The tendency of the material will be to fill up the hollows and depressions, in consequence of which the sheet, while gradually tapering from the shore-line seaward, will be thickest in the hollows and thinnest on the ridges. In other words, the first sheet of material will conform to the contour of the floor on which it rests.

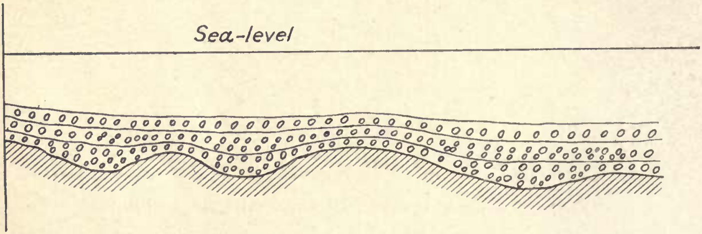


Fig. 51.—Showing parallelism of beds after the hollows in the sea-floor are filled up.

The next sheet of detritus will be spread over the first, but the hollows will receive a thicker coating than the other portions of the floor. As layer after layer is laid down, the hollows will be completely filled up; and after that happens, the succeeding layers will be parallel throughout.

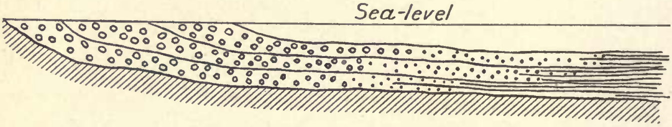


Fig. 52.—Showing seaward overlap as a result of deposition on a stationary or rising sea-floor.

On a gently shelving sea-floor, when the level of the land relatively to the sea is stationary, or when the land is rising slowly, the detritus is carried further and further seaward, with the result that the successive zones of sorted material do not lie vertically above one another, but *overlap* going *seaward*, the upper sheets overlapping the lower as shown in fig. 52. The result of this overlapping is that different grades of material succeed one another in a vertical line. Thus a bed or stratum of mud may be followed by a bed of sand, and a bed of sand by one of gravel. This alternation of different grades of material produces, when consolidation takes place, what is known as *stratification*.

Alternations of thin beds of sandstone and thinner beds of slaty shale are frequently seen among the older rock-formations, and this alternation may persist through a thickness of many thousand feet. In this case the deposition of fine silt or mud on the sands may have been due to small seasonal variations in the velocity of the sea-currents, or to the seasonal changes in the prevailing winds, exercising an influence on the direction and strength of the currents, or to the varying power of the tides.

Theoretically, a conglomerate which is a shore-line deposit ought to graduate going seaward into a sandstone, and from a sandstone into a mudstone; but owing to the mixing up of the material through coastal currents and gales at the time of deposition, this condition is perhaps seldom found to exist in nature.

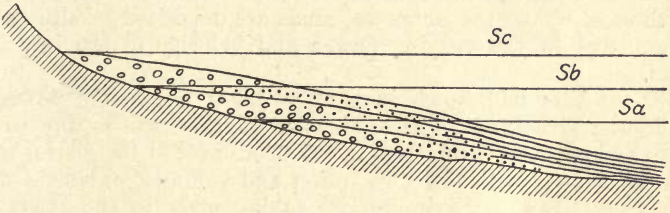


FIG. 53.—Showing landward overlap as the result of deposition of detritus on sinking sea-floor.

Sa, *Sb*, and *Sc* mark successive sea-levels.

On a sinking shore-line with an advancing sea, the overlap of the successive layers of detritus laid down on the sea-floor will be on the *landward* side as shown in the next figure.

Lamination.—When a rock occurs in very thin layers it is said to be *laminated*. The *laminæ* may vary from the hundredth of an inch to an inch thick. A laminated structure is only found in rocks composed of silt or mud. The laminæ frequently vary in colour. Thus one lamina may be greyish blue; another greenish grey, yellowish brown, or red. Alternating laminæ of different colours give the rock a ribbon-like appearance when viewed in sectional elevation.

Glacial clays, shales, and slates frequently possess a laminated structure. These are composed of the fine sediments carried by rivers into seas and lakes, being deposited where there is little or no movement in the water, or of muds spread over the floor of estuaries and tidal harbours.

Investigation has shown that the lamination, even when paper-like, is due to minute differences in the size of the particles. The process of deposition of very thin layers is, like stratification, dependent on the principle of *equal falling particles*. Let us assume that a silt-laden river like the Amazon enters the sea with a velocity of one foot per second. It is obvious that the suspended particles will settle on the sea-floor in parallel zones, the coarser silts first and the finest furthest seaward. But if through any cause, such as the daily pulsations of the tides, the velocity of the current is checked, we shall get frequent alternations of normal flow and slack-water, with the obvious result that in any certain zone there will be deposited alternating layers or laminæ of fine and excessively fine silt, laid down one above another. This process of lamination can be seen in operation in all of our mud-filled tidal harbours. In these also near the entrance, muds are deposited in alternating layers, due to the varying power and velocity of the inrushing tides.

Glacial silts laid down in shallow lakes frequently possess a laminated structure. The lamination in this case is due to the daily and seasonal variations in the flood-level of the glacial river. Glacial rivers, particularly in spring and summer, exhibit a daily rise and fall, the maximum rise taking place in the afternoon. The velocity of flow varies with the depth of the water, and in consequence we get at the point of discharge an overlapping of sediments of different grades which, as we have seen, induces the structure termed *lamination*.

Laminated rocks generally split readily in a direction parallel to the plane of the laminæ. The presence of finely comminuted flakes of mica adds greatly to the ease with which the splitting takes place.

The differences in colour frequently met with in laminated rocks is due to slight variations in the composition of the sediments laid down at various times or seasons. A river like the Amazon drains nearly half a continent. Many rock-formations are represented within its watershed. The large tributaries are not always in flood at the same times. Thus one tributary may, when in flood, contribute chalky muds, and another tributary slaty or micaceous silt. In this way the alternation of different-coloured sediments is obtained.

Lamination is thus seen to be merely a minute form of stratification, mainly, but not exclusively, the work of water. The dust ejected from the great fissure-rent during the Tarawera eruption in 1886 was a mixture of various grades of fine material. In many places it settled in thin laminæ, the sorting into uniform grades of equal-falling particles being effected by the winnowing action of the high wind prevailing at the time. The wind did not maintain a steady pressure, but came in powerful blasts, which thus allowed layers of dust of different fineness to settle one after another in the same zone.

The sands forming coastal dunes frequently possess a laminated or banded structure, also due to the varying velocity of the prevailing winds.

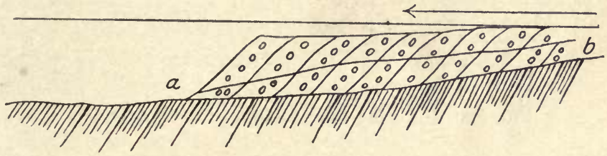


Fig. 54.—Showing formation of false-bedding at head of lake.

False-Bedding.—This is a bedding that does not lie parallel to the general bedding plane of the formation in which it occurs. It is frequently found in sands and fine gravels deposited on the bed of the sea, on the floor of a lake, or in the channel of a river; and is frequently a quite local phenomenon. *False-bedding*, also termed *current-bedding*, can be frequently seen in process of formation at the head of valley-lakes that are being filled up with river detritus, and also in the broad shingle beds of mountain streams.

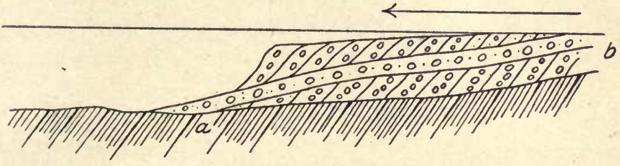


Fig. 55.—Showing false-bedding in lacustrine detritus poured into a lake-basin.

The gravels and sands, as they are discharged into the lake-basin in times of normal flow, are laid down in an inclined position like the material tipped from trucks at the end of a mine-dump. During floods, the river acquires a greater velocity and is thereby enabled to cut away the crest of the detritus previously laid down at the head of the lake. As the flood slackens, a sheet of detritus is laid over the truncated edges of the inclined beds *a–b*; and when the flood finally subsides and normal conditions prevail, the fresh material discharged by the river is once more laid down in the now almost still water in an inclined position like the first, and we get the appearance shown in fig. 55.

It should be here noted that the detritus is not carried in suspension, but is rolled along the bottom until it reaches the edge of the *tip*, where it rolls down, at once adjusting itself to the natural angle of rest.

False-bedding is frequently seen in loose river gravels at places where holes are scoured in the bed, or old shallow channels have been gradually filled up by the tipping process mentioned above. When filled up to the normal flood-plane, the inclined beds tipped into the depression are overspread with sheets of gravel lying parallel to the plane of flow.

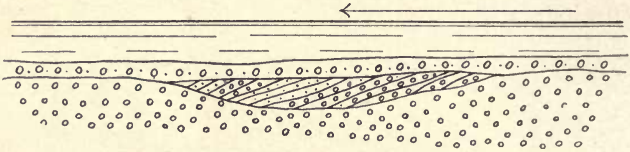


Fig. 56.—Showing false-bedding in river-gravels.

False-bedding is also seen in river-gravels laid down in what is termed a *back-water* or elongated eddy in which the current runs in the opposite direction to that of the general flow of the stream.

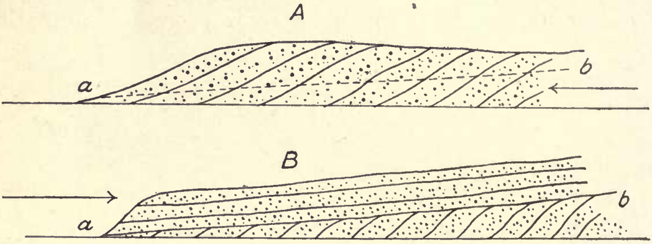


Fig. 57.—Showing false-bedding in wind-blown sands.

The false-bedding of estuarine or fluvio-marine sediments is of frequent occurrence. It generally takes place in the same manner as in lacustrine deposits, and is more often seen in sandy beds than in conglomerates.

Wind-blown sands frequently exhibit fine examples of false-bedding. The sand is driven along before the wind until it reaches the lee-side of a ridge or edge of a declivity where it immediately falls down the sheltered slope, forming layers more or less parallel with the angle of rest, as shown in A of fig. 57, in which the direction of the wind is indicated by the arrow.

When the wind blows from the opposite direction, the crests of the inclined layers of sand are liable to be truncated along the line *a–b*. When this happens, fresh layers of sand are sometimes, but not always, laid down in a nearly horizontal plane, as shown in B, fig. 57. It sometimes happens that the wind after truncating the inclined layers begins to build up a new set of layers inclined towards the direction in which the wind is travelling.

Current-laid Stones.—In rivers, and in all currents of water that run continually in the same direction, the larger stones, particularly those of a slabby shape, tend to arrange themselves in such a way as to offer the greatest resistance to the water flowing over them (fig. 58). This arrangement can be seen in almost every gravel terrace composed of layers of fine and coarse gravel. It always affords a valuable clue to the gold-miner as to the direction of flow of the ancient river that formed the terrace, thereby enabling him to locate with some degree of certainty the position of the gold-bearing wash-dirt.

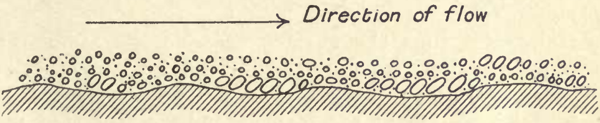


Fig. 58.—Showing arrangement of stones in a river-bed to resist being lifted.

Surface Markings on Sediments.

From our study of the manner in which sediments are formed on the sea-floor, we are able to deduce two fundamental truths that have an extraordinary importance in connection with the unravelling of the history of the Earth. These truths, which are now recognised as geological axioms, may be expressed as under :—

(1) That all mechanically formed sediments are composed of the waste of pre-existing land.

(2) That all marine detrital sediments were laid down marginal to land areas.

Hence, in his endeavour to trace out the geographical distribution of the land and sea at the different stages of the Earth's history, the geologist searches for all the evidences that indicate the former existence of shore-line conditions of deposition.

The most trustworthy and tangible evidences of ancient shorelines are beds of conglomerate composed of beach-shingle, and rocks containing the remains of marine life that are known to live only in shallow water. These outstanding and indestructible proofs are frequently supplemented by facts that may in themselves appear insignificant, but are not less valuable in affording clues as to conditions of deposition on which special emphasis may be safely laid.

Among these minor proofs are *ripple-marks*, *sun-cracks*, *rain- and hail-prints*, and *animal trails*, all of which have been found in rocks composed of sediments of fine texture.

Ripple-Marks.—These may be frequently seen in the sands laid down on the sandy shore of a lake or sea, or on the floor of a shallow lake or estuary. They are produced by the pulsations of a slowly retreating tide. They are also formed by the wind bearing on the surface of shallow, slowly-ebbing, tidal waters. The ripple-marks produced by one ebbing tide will be obliterated by the next flowing tide, which, on retreating, will form a new series of ripples.

In certain situations the surface of sand dunes is frequently covered with parallel ripple-marks formed by oscillations in the force of the wind.

Where the ripple-marks are formed under water that is always receiving fresh accessions of sand, a ripple-marked surface may be gently overspread with a layer of sand and be thus preserved (Plate XII.). Ripple-marked sandstones are found among the geological formations of all ages.

Sun-Cracks.—In many shallow tidal harbours, estuaries, and deltas, a marginal strip of silt or mud is daily left high and dry between the high-water and low-water lines. At the upper limits of the tide the sediments may be exposed to the drying influence of the sun's rays for many hours at a time ; and when this happens the muds shrink, and in doing so become seamed with a network of cracks that produce polygonal cakes somewhat resembling the pattern of an ancient Roman pavement.

Sun-cracked muds are a striking feature in many mangrove-covered tidal harbours in north New Zealand, Australia, East Indies, and other tropical and semi-tropical lands where the blazing heat of the summer sun at certain phases of the tide dries up the marginal layers of mud with great rapidity. The same phenomenon on a miniature scale may be witnessed in almost all temperate lands in dried-up mud-puddles and pools on the roadside, and in cultivated fields after heavy rain followed by sunshine or a drying wind.

Estuarine and tidal sun-cracks are generally obliterated by the

RIPPLE-MARKS IN BURKE FORMATION ON TIGER PEAK. (U.S. Geol. Survey.)

next tide, but in some cases they are gently filled with fine sediment and thereby preserved. Fossil sun-cracks are eloquent witnesses of tidal muds and a blazing sun in past geological ages.

Rain- and Hail-Prints.—Estuarine muds are sometimes pitted with the heavy drops of a passing shower of hail or rain, and when these prints are gently covered with mud by a slowly rising tide they are permanently preserved, thus forming valuable meteorological records.

Where the mud is very soft, the rain only makes indistinct splashes, and where it is too hard, it fails to make any impression. But in tropical and semi-tropical lands, the hail frequently falls as large as hazel-nuts. In a few minutes it litters the ground with leaves stripped from the fringing mangrove trees, and in the open estuary descends with such force that much of it is half-buried in the mud. When the half-buried hail melts, it leaves perfect dimples or prints scattered irregularly over the surface of the mud. Many, if not the majority, of the supposed fossil rain-prints are probably hail-prints.

Fig. 59.—Showing sun-cracks in harbour mud.

Fossil-prints have been found in many geological formations, and their values lie in the proofs they afford that the meteorological conditions of to-day are but a continuance of those that existed in far-off geological times.

Animal Trails.—Crabs, lobsters, shellfish, and worms as they move over the surface of the partially dried silts and muds exposed between tide-marks, leave their trails and burrows, which, under favourable circumstances, may be preserved by a fresh layer of sediment. Marks such as these have been found in rocks composed of fine sand and mud; and are regarded with much interest by geologists as they afford conclusive proof of the physical conditions under which the sediments were laid down.

Besides these, there have also been preserved in slabs of stone the tracks of reptiles, birds, and mammals that in past ages roamed about the margins of the sun-dried estuaries and deltas in search of food.

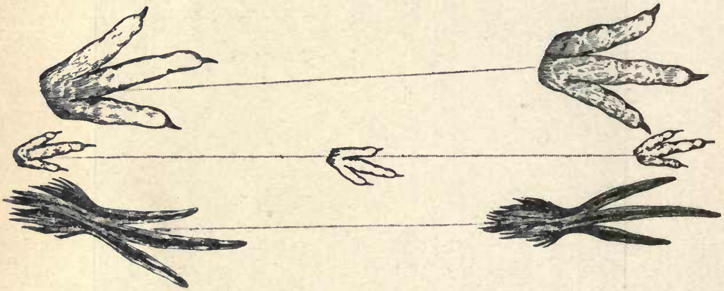
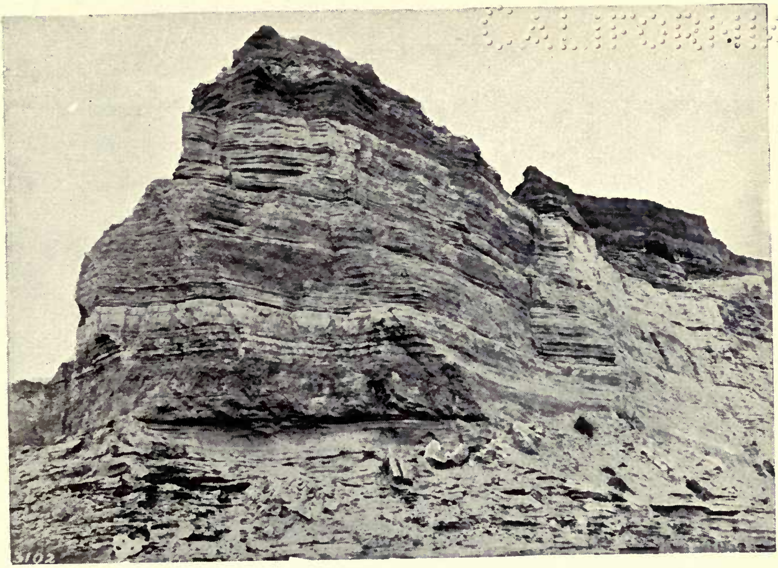


FIG. 60.—Showing animal tracks.

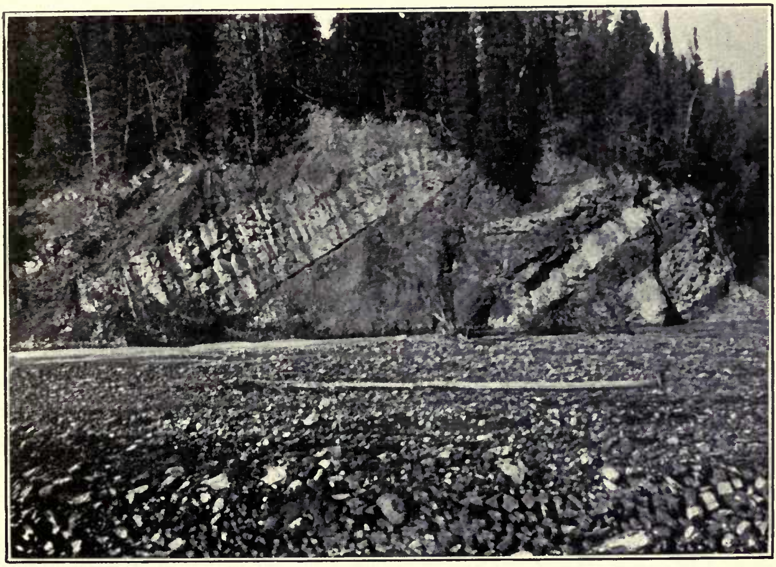
SUMMARY.

The rock-structures that have been considered in this chapter are (1) *Stratification*, (2) *Lamination*, and (3) *False-bedding*.

(1) *Stratification* refers to the arrangement of detrital material in parallel layers or beds commonly termed *strata*; a word derived from the Latin *stratum* = a layer or bed. When the different beds (exposed for example in a sea-cliff) are distinctly marked, the rocks are said to be *well-stratified*. But if, on the other hand, the bedding is indistinct and difficult to determine, the rock is said to be *indistinctly stratified*. Thin bands of any material occurring at intervals in a formation that possesses no bedding planes, always impart a stratified appearance to the rock. A line of detached nodules or pebbles will also indicate the original deposition plane in a rock that otherwise shows no evidence of bedding.



A. HORIZONTAL PLIOCENE STRATA, NEW ZEALAND.



B. INCLINED STRATA.

The appearance of well-stratified rocks as seen in many sea-cliffs is shown in fig. 61, and in Plate XIII. (A).

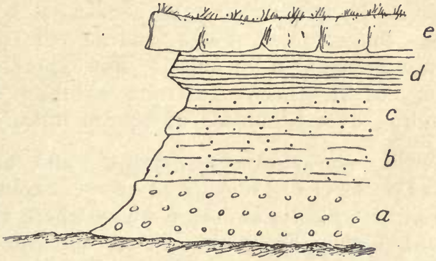


Fig. 61.—Showing section of stratified rocks.

(*a*) Conglomerate.
(*b*) Thick-bedded sandstone.
(*c*) Thin-bedded sandstone.
(*d*) Marly clays.
(*e*) Marine limestone.

(2) *Lamination* refers to the aqueous deposition of silt and mud in very thin layers or *laminæ.* Lamination is merely a minute form of stratification, and is a structure found only in fine sediments deposited in still or slowly moving waters in accordance with the principle of equal-falling particles.

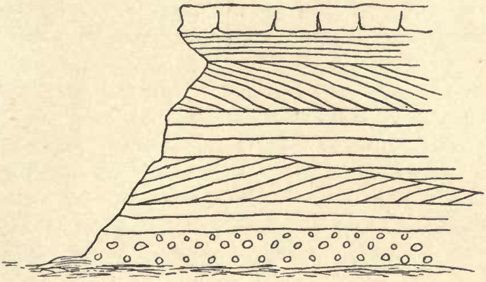


Fig. 62.—Showing false-bedding structure.

(3) When the planes of stratification in some particular bed run at some other angle than the general plane of the beds above and below, the structure is termed *false-bedding* or *current-bedding.*

The appearance of false-bedding in consolidated or partially consolidated rocks is shown in fig. 62.

False-bedding is found in fluviatile, lacustrine, and marine deposits, as well as in wind-blown sands. It is frequently a local phenomenon due to the action of eddies, back-water currents, and the tipping of sediments into comparatively still deep water. It should, however, be noted that false-bedding is not necessarily limited to local occurrences. False-bedding can sometimes be traced in a particular stratum for miles, For example, the famous *Desert Sandstone* of Northern Australia exhibits this peculiar structure extending over hundreds of square miles.

(4) Ripple-marks, sun-cracks, rain-prints, and animal tracks are found preserved in rocks, and afford conclusive evidence of shore-line conditions at the place where the sediments were laid down. They also afford valuable evidence as to the meteorological conditions of far-away geological ages.

(5) It is a geological axiom that all the mechanically formed sediments laid down on the floor of the sea were formed of the waste of pre-existing land.

(6) Another axiom of extraordinary value in solving problems relating to the distribution of land and sea in the past geological ages is that all sediments laid down on the sea-floor were marginal to land areas existing at the time.

CHAPTER VIII.

ROCK STRUCTURES.

THE CONSOLIDATION OF SEDIMENTS.

IN the last chapter we were principally concerned with the manner in which the products of denudation in the form of coarse and fine sediments were spread out in parallel layers and piled up on the sea-floor and in lake-basins. These sediments are the materials of which stratified rocks are formed.

When we speak of a rock we at once form a mental picture of something hard and compact. As a matter of fact, some rocks are very soft and others very hard. A marl or clay, for example, is very soft and friable; while a sandstone may be intensely hard.

Sedimentary rocks, as generally defined, are composed of sediments that are more or less *hardened* or *consolidated*; and although originally laid down in a horizontal or approximately horizontal position, they are now found to be *tilted* or *inclined* at various angles, and thrown into *folds* that may be gentle *undulations* or minute *corrugations*.

Moreover, closer examination soon discloses the fact that the rocks have not only been pushed into folds and corrugations, but also *fissured* with many small *cracks* or *joints*, and occasionally traversed by great *dislocations* or *fractures* termed *faults*.

Everywhere there is evidence that the rocks have been at one time or another subjected to enormous *stress* or *pressure* whereby they have been folded, crumpled, tilted, fissured, or fractured as mentioned above.

Our aim in this chapter will be to consider the various processes by which soft and incoherent sediments may be consolidated or hardened into what is called rock.

Hardening of Sediments.

The hardening of sediments may be effected (*a*) by *pressure* or (*b*) by a *cementing medium*.

Hardening by Pressure.—This is the simplest and most obvious means of consolidation, and whether the pressure is effected by natural or artificial agency, the results are always the same. Thus, when clay is placed in a mould and subjected to great pressure, it is compressed, partially dehydrated, and converted into a brick or tile as compact as an ordinary shale.

The same thing takes place in Nature. When clay, mud, or fine silt is subjected to the pressure of hundreds of feet of overlying sediment, it is converted into a shale or claystone.

Coarse sediments are not easily consolidated by mere pressure alone; but if they consist of particles of various sizes that will fill up the interstices between the larger grains or pebbles, or if they contain an admixture of muddy paste, they may be consolidated into a fairly hard rock by pressure alone.

The principle underlying consolidation by pressure is that fine sediments afford a larger adhesive surface relatively to the size of the constituent particles than coarse sediments.

Hardening by a Cementing Medium.—The process of hardening by a cementing medium may be easily illustrated by a simple experiment. Take *four* ounces of Portland cement, *six* ounces of clean sand, and *six* ounces of pebbles the size of peas.

Place these constituents on a flat plate or board and mix thoroughly in a dry state.

Pile the mixture into the form of a flat truncated cone. Make a hole in the middle of the cone and into it pour *two* ounces of clean water.

With two spatulas, one in each hand, work the mixture and water into a thick paste, adding a *little* more water if required. Turn the paste over for several minutes until the water is thoroughly incorporated, and then press it firmly into a mould of any shape. A small cigar-box will do very well. After two or three hours remove the hardened mass from the box and you will have a slab of hard rock artificially formed.

This experiment is not intended to illustrate the chemical process of setting so much as the part played by the cement in binding the sand and grit into a hard aggregate. The cement is merely an artificial *matrix* in which the sand and grit are embedded. If moistened with water and placed in the mould, it would form a slab of fine-grained artificial stone much stronger than that obtained in our experiment.

In the making of concrete, which is merely an artificial stone, it is found that the greater the proportion of constituent aggregates, such as sand, gravel, or broken rock, to the cement or matrix, the weaker is the resulting concrete; and such also is found to be the case in Nature.

Take again the case of the frozen gold-bearing gravels in Siberia, Alaska, and Alpine New Zealand. The contained water freezes for a depth of a few inches or many feet, according to the length and severity of the winter frosts, and hardens the whole mass into a rock-like mass resembling a conglomerate. Here the frozen water is the cementing medium or *matrix*, and although the hardening is only *temporary* it very well illustrates the formation of conglomerates.

The permanent hardening of sediments by a cementing medium is effected in Nature by the deposition of mineral matter between the constituent particles from waters slowly circulating through the mass.

The commonest natural cementing media are *carbonate of lime*, *oxide of iron*, and *silica*.

Carbonate of lime and some *iron compounds* are soluble in water charged with carbonic acid gas, and these may be deposited as carbonates if the water evaporates, or if the carbonic acid becomes disengaged as it does quite readily, being what is known as a weak acid—that is an acid which possesses but a feeble hold of the substances with which it combines.

The deposit or precipitate of carbonate of lime or iron acts as a cementing medium and binds the surrounding particles into a coherent mass. In this way sands are converted into sandstones, and gravels into conglomerates.

When the carbonate of iron is deposited among porous sands or gravels, it becomes in the presence of water converted into the rusty brown hydrous oxide called *limonite*. Hence we find that the cementing medium of ferruginous sandstones, gritstones, and conglomerates is in almost all cases the hydrous oxide of iron.

On the other hand, when carbonate of iron is precipitated in a fine impervious sediment, it remains as the carbonate, forming the well-known clay-band ironstone—a valuable ore of iron that occurs in formations of all geological ages.

Silica is perhaps more abundant as a cementing matrix than carbonate of lime, particularly among the older rocks. It is soluble in waters containing potash or soda, especially at high temperatures. Deep-seated waters are generally *alkaline* from the presence of dissolved salts of potash or soda. These waters in their passage through the rocks dissolve silica, and when they come to the surface or when they reach a cooler stratum, the silica is deposited around and between the particles, which are thereby cemented into a compact rock.

Siliceous waters are frequently abundant in volcanic regions of waning activity, where they appear in the form of hot springs and geysers. The potash or soda has a greater liking or affinity for the carbonic acid of the atmosphere than for the silica. It consequently forms a new partnership, thereby liberating the silica which is deposited as an incrustation of sinter around the outlet of the spring or geyser from which the waters issue. Moreover, sands and gravels that happen to lie near are cemented into hard rock.

These siliceous waters also possess a petrifying power, such organic substances as leaves, twigs, and even animal remains being replaced by silica, the replacement taking place so slowly as frequently to reproduce in stone the exact form and structure of the original organism.

From the foregoing we find that a stratum of sand may be cemented with carbonate of lime, oxide of iron, or silica.

The carbonate of lime forms a *calcareous sandstone* ; the oxide of iron, a *ferruginous* or *limonitic sandstone* ; and silica, a *siliceous sandstone.* That is, the nature of the sandstone and of the qualifying adjective depends on the character of the cementing matrix. Similarly, we may have a *calcareous conglomerate*, a *limonitic conglomerate*, or a *siliceous conglomerate.*

When a pile of sediments consists of alternating layers of mud and sands, the sandy beds are in many cases found to be cemented into a hard resistant rock, while the layers of mud or clay remain relatively soft. Such hard bands may be seen standing out as projecting ledges in many sea-cliffs and scarps.

The hardening of the sandy beds was in most cases due to the deposition in them of a cementing medium. The clayey beds being impervious to water only attained the moderate degree of hardness that could be imparted by pressure and dehydration ; whereas the sandy beds being porous offered a free passage for the flow of the mineralised waters which left behind them a deposit of cementing material.

The coral reefs and coralline beach-sands of the tropics, as well as the shelly sands and shell-banks found on the strands of nearly all lands, have been in many places converted into compact limestones by the partial or complete dissolution and replacement of the corals and shells by carbonate of lime in a semi-crystalline or crystalline form in which there is generally no trace of the original organisms.

Other Cementing Media.—Among other, but less common, cementing materials deposited among sediments by mineralised waters are *carbonate of magnesia*, *sulphate of lime*, *sulphate of barium*, and *oxides of manganese.*

Carbonate of lime is a comparatively soft substance ; consequently the rocks in which it is the cementing medium are seldom capable of withstanding much wear and tear. On the other hand, silica is an exceeding hard substance, and hence siliceous sandstones and conglomerates are always hard rocks capable of withstanding a great amount of mechanical or chemical erosion.

Limonitic sandstones are frequently soft and friable, but many limonitic quartz conglomerates and grits possess great resisting power.

Concretions.—It frequently happens that only isolated portions of a bed or stratum are hardened by the cementing medium. These hardened portions or *concretions* have been formed where the supply of carbonate of lime or evaporation has been greatest. They may occur close together or widely scattered.

Concretions[1] are generally spheroidal in form, and for that reason are sometimes mistaken for pebbles or water-worn boulders. They may range in size from a few inches up to ten feet or more in diameter. They are frequently composed of concentric layers that peel off like the layers of an onion until a solid spheroidal core is reached. This spheroid on close examination is frequently found to have formed round some organic body, such as a shell or saurian bone, as a nucleus.

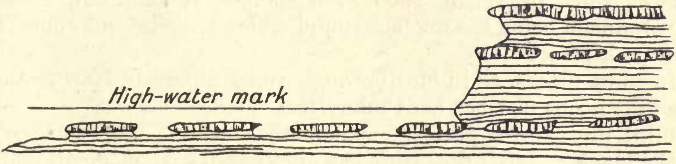


FIG. 63.—Showing tabular concretions.

In many cases the internal portion of the concretion has contracted more than the external, thereby giving rise to numerous radiating cracks that have subsequently become filled with calcite. Concretions possessing this structure are sometimes called *septarian boulders*, or simply *septaria*.

Concretions are commonly found in shales and clays. They are especially abundant in the shaly clays of the Cretaceous Period in many parts of the globe.

Concretions in which carbonate of iron is the cementing medium are sometimes quite common in clays and shales, but they seldom attain the dimensions of septaria.

Clays sometimes contain nodular-shaped concretions composed of limestone, oxide of iron, or iron pyrites. These concretions frequently assume grotesque forms that sometimes bear a quaint

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[1] From the Latin *con* = together, and *cretus* = grown.

resemblance to organic bodies or to objects fashioned by the hand of primitive man. Many of these nodules are hollow, the cavity being lined with crystals.

The hardened portions of a stratum are frequently lenticular or tabular in form, and lie so close together as almost to form a continuous band of hard rock, as shown in fig. 63 on p. 129. This structure is due to the separation of the carbonate of lime from the remainder of the rock, and its aggregation in layers or tabular masses.

Some concretions were probably formed during the accumulation of the sediments in which they lie, but the majority have arisen from a rearrangement and concentration of like kinds of mineral matter.

Flints.—These occur as grey and black nodules dispersed in certain layers in the Upper Chalk of England, north-west Europe, America, and New Zealand, and elsewhere. They frequently enclose some organism, such as a sponge, echinoderm, or shell, the organism being the nucleus round which the siliceous concentration took place.

In some places, as in Marlborough and Kaipara in New Zealand, the flint forms distinct beds many feet thick.

Flint possesses a perfect conchoidal fracture. The dark colour of the black variety arises from the presence of carbonaceous matter, which can be dispelled by heat.

Flint nodules are formed by the interchange of carbonate of lime and silica. Many marine plants and animals secrete silica from sea-water for the building up of their organisms. The water present in the chalk dissolves these organisms, and as it does so, replaces them with carbonate of lime. The water now charged with silica deposits the silica elsewhere, preferably where some of it already exists, as, for example, on sponge-skeletons, which consist of siliceous spicules.

In cases where the calcareous shell of an echinoderm or a coral has been replaced by silica, it would seem that the dissolution of the carbonate of lime was accompanied by direct replacement with silica, molecule by molecule, the process being similar to the replacement of shells by iron pyrites, which has so frequently taken place in clays and shales.

Such replacement of one mineral by another is called *pseudomorphism*.[1]

Fulgurites.—As a geological agent lightning is not of much importance. It is reputed to be capable of shattering solid rocks, but its usual effect is to perforate their surface with small holes lined with a glassy enamel. When the electric spark is discharged

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[1] From the Gr. *pseudos* = false, and *morphe* = form.

into sand or loose soil, it may form short, tapering, fragile tubes of partially fused sand-grains called *fulgurites*; or blebs of well-fused glass, usually shaped like buttons or dumbbells. From their prevalence in the desert regions of Australia these fused blebs or drops have been called *Australites*.

CHAPTER IX.

EARTH-MOVEMENTS.

EARTH-MOVEMENT may take the form of uplift or subsidence, rock-folding or faulting, shearing or horizontal displacement. Moreover, it may be *local* or *continental, slow* or *rapid.*

Local movements are usually due to volcanic agency, earthquakes, or faulting. They are relatively rapid, and may cause sharp folding and faulting of strata in the neighbourhood of the disturbance.

The movement which affects continents or large areas is usually slow, and may not amount to more than a few inches in a century. Such slow regional movement is called *secular movement*, as it is more or less continuous over a number of years.

An upward crustal movement, which eventually results in the formation or building up of a land-surface of continental dimensions, is called *epeirogenic*; while an upward linear folding of the strata, which eventually uplifts mountain-chains, is called *orogenic.*[1]

SLOW ELEVATION AND SUBSIDENCE OF THE LAND.

Elevation.

When we find strata containing marine shells forming masses of dry land, hundreds or may be thousands of feet above the sea-level datum, we are compelled to conclude that the land has emerged from the sea. These shelly beds represent the uplifted sea-floor of some past geological age.

Among the best evidences of recent uplift are what are called *raised-beaches,* which is only another name for uplifted sea-strands. These occur on the shores of many lands in both hemispheres, being strikingly conspicuous on the coasts of Scotland, England, Norway, Sweden, Spain, South Italy, Sicily, Morocco, Algeria, Egypt, Pacific side of North and South America, India, Australia, and New Zealand. They form benches or terraces that in some cases can be traced along the coast-line for scores and even hundreds of miles,

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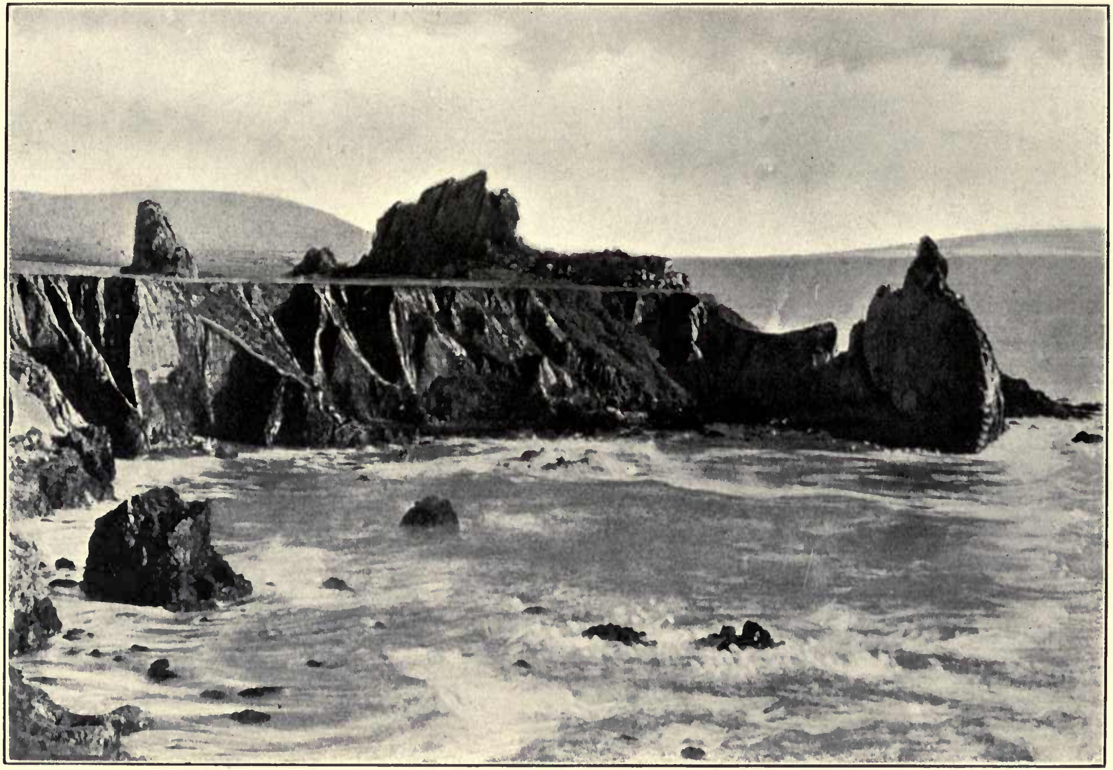
[1] Gr. *oros* = a mountain, and *genesis* = production.



RAISED WAVE-CUT MARINE TERRACE, NORTH OF PORT HARFORD, CALIFORNIA.

curving round headlands and following the various indentations of deep bays and long fiords.

Raised-beaches consist of shingle and sand mixed with sea-shells, the majority of which belong to species still living in the adjacent seas. They are generally backed by cliffs that are frequently wave-worn and undercut or hollowed into caves. In some cases the rocks are covered with barnacles or perforated with holes bored by marine shells.

In the fiords of Norway the raised-beaches occur at heights varying from 50 to 600 feet above the sea, and singularly enough they are not horizontal but slope gently towards the sea, which is an evidence that the rate of uplift is more rapid on the landward than seaward side. This unequal rate is what is termed *differential uplift.*

In Scotland raised-beaches can be traced at 25, 40, 50, 60, 75, and 100 feet above the present sea-level.

The occurrence of marine shells in rocks involved in the great earth-folds which comprise the Alps, Himalayas, and other mountain-chains, affords incontestable proof of uplift in bygone geological times. Raised beaches are records of comparatively recent elevation; and we have abundant evidence that elevation is still in progress in some parts of the globe. It is doubtful if the land is ever in a state of complete rest for any considerable time. If it is not rising, it is probably sinking; and it frequently happens that uplift on one side of a continent is compensated by subsidence on the other. Marks placed on the coast of Sweden in 1820 have shown that the land is still rising at the rate of 2 or 3 feet in a century.

Subsidence.

The evidences of subsidence are not always so obvious as those of uplift, as they are mostly to be found submerged in the sea. Among the most conclusive proofs are submerged coal-seams, submerged forests, and buildings. To these might be added the formation of atolls and drowned valleys.

Submerged Coals.—At the present time seams of coal are being worked many hundred feet below sea-level in New South Wales and New Zealand. Now coal, as we know, consists of the remains of vegetation that required sunshine and air for its growth. It was formed on the dry land, and is what is called a *terrestrial deposit.* When, therefore, we find it hundreds and in some cases thousands of feet below the present level of the sea, we are safe in concluding that a subsidence of the old land-surface, on which the coal vegetation grew, has taken place at some remote period.

Submerged Forests.—The erect stumps of forest trees, frequently associated with peaty matter containing twigs, leaves, and fruits, are found below sea-level in many lands. Good examples are seen at Formby Point on the coast of Lancashire; at Leasowe, in Cheshire; and at Freshwater West, in Pembrokeshire. Such submerged forests are an evidence of subsidence in quite late geological times or of coastal sag.

Drowned Valleys.—The celebrated fiords of Norway and New Zealand, that stretch far back among the neighbouring mountain-chains, are merely valleys that have been invaded by the sea. In California and other lands the soundings show that some of the existing valleys can still be traced far seaward. That is, river-valleys are found to be continuous with valleys in the sea-floor. This is rightly held to be proof of comparatively recent subsidence of the coast-line.

The broken, deeply indented, and ragged coasts of British Columbia, Alaska, North-East Canada, and Greenland have originated from a general subsidence of the previously deeply dissected maritime lands in these regions.

Barrier Reefs and Atolls.—According to Darwin's view, these are coral reefs that have grown upward on a sinking sea-floor. The borings conducted at the island of Funafuti proved the existence of coral reefs and coral limestone down to a depth of 1114 feet below sea-level; and since the coral polyp can only live in comparatively shallow water, extensive subsidence, probably amounting to 800 feet, must have taken place since the foundations of the existing coral reefs were formed by the coral-builders.

Rapid Earth-Movement.

Earthquakes may be due to the sudden jolts arising from the settlement of the ground along the plane of great faults or dislocations in the crust, or they may be propagated by sudden subterranean explosions of steam during a volcanic eruption.

Shocks of great intensity may crack and overthrow buildings, fracture rocks, fissure the ground, propagate earth-waves and tidal waves.

Earthquakes that originate at fault-planes may throw down forests, shatter rocks, and cause other destruction for hundreds of miles along the line of fracture or dislocation. Shocks resulting from volcanic explosions are frequently sharp and destructive, but the effects are generally local and confined to the volcanic zone, which may be bounded by fault-planes.

The standing pillars of the Temple of Jupiter Serapis in the Bay of Baiae, a few miles north of Naples, are an example of the extreme steadiness of the subsidence and elevation that may take place even in a volcanic region where the movement is relatively rapid.

The ruins stand within a stone's-throw of the water's edge, and on all sides are extinct craters. Less than a mile to the north-east lies the well-known crater of Solfatara, still in the expiring stages of volcanic activity ; and about two miles to the north-west is the beautifully symmetrical cone of Monte Nuovo.

Three standing marble pillars rise from a level pavement. About 10½ feet from the base the columns are pitted with holes made by boring molluscs. The length of column pitted in this way is a little over 8 feet. Near the top of the perforated portion there is a slight annular indentation, in all probability the work of marine corrosion, which would indicate that the land remained stationary at that point for some time.

The presence of the borings proves that the pillars must have been submerged in sea-water for some considerable time and afterwards elevated to their present level. The original height of the temple above sea-level is not known. The level of the platform is still a little below high-water mark, and a second platform exists 5 feet below the first, indicating that an earlier subsidence had rendered it necessary to construct a new floor at a higher level. Therefore, within historic times, we have proof of an up-and-down vertical movement amounting to 45 feet, on the assumption that the original lower floor was only 2 feet above high-water mark when first constructed.

Raised shelly strands and other evidences of recent elevation may be seen all along the west coast of Italy as far south as the Straits of Messina ; and similar evidences of elevation are found on the shores of Tunis and Algeria.

Thus, as between the east and west coasts of Italy we have a tilting movement in progress, the axis of which runs parallel with the peninsula. The Adriatic shores of Italy, however, are undergoing submergence.

The most recent uplift of which we have authentic evidence took place during the great Yukutat earthquake in Alaska, in September 1899, as the result of displacement along pre-existing fault-planes. The vertical uplift varied from 7 to 47 feet, as attested by the presence of barnacles and bunches of mussel shells attached to the ledges of rock high above the present tide-mark.

Tilting of Strata.

Dip.—When a bed or stratum is tilted so as to be inclined in some direction, the *direction* of the inclination is called the dip ;

and it is always the steepest line of the inclined surface that shows the true direction of the dip.

The amount of the inclination, or the *angle of dip* as it is generally called, is always measured from the plane of the horizon.

Thus we have :—

The direction of inclination = dip.

The amount of inclination = angle of dip measured from the plane of the horizon.

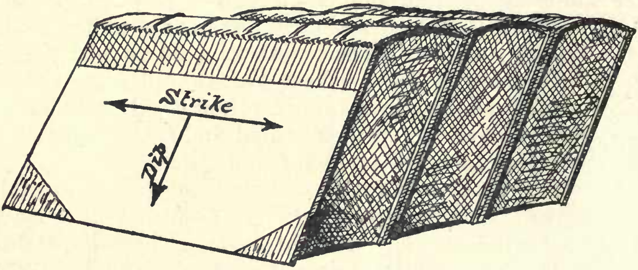


FIG. 64.—To illustrate dip and strike of strata.

The *direction* as well as the *amount* of the dip is always observed and recorded. The direction of the dip is determined with a *compass*, and the amount of dip with a *clinometer*. The ordinary geological box-compass is generally provided with a pendulum-bob for recording angles of inclination on a graduated scale.

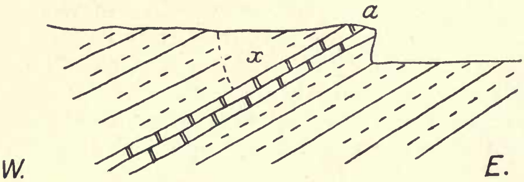


FIG. 65.—Showing angle of dip = x.

The amount of the dip may vary from 0° to 90°. At 90° the beds are said to be *vertical*.

In fig. 65 the bed of limestone marked *a* dips to the *west* at an angle of inclination = x.

Strike.—The horizontal line along the tilted stratum is called the *strike*, and it is always at right angles to the dip.

In metalliferous mining the strike of a lode is commonly spoken of as the *course* of the lode. So that the horizontal direction pursued by the course of a lode or bed is the strike. If, for example, a seam of coal or a metalliferous lode crops out on a plain or level ridge, the line joining the various outcrops is the line of strike or course of the seam or lode.

If a tent-fly raised on a ridge-pole be taken to represent a folded stratum of rock, then the direction in which the ridge lies will represent the strike.

Furthermore, if the tent-fly represents an anticline, then the ridge is the *axis* of the anticline, as previously described.

Folding of Strata.

The majority of sedimentary or clastic rocks were laid down as horizontal layers on the floor of some sea or lake. When, therefore, we find such rocks forming hills and high mountain-chains, we are compelled to conclude that they have been elevated by some powerful agency. And when on closer examination we find that these strata are not always horizontal, but in many places tilted and folded, we are further compelled to conclude that they have been subjected to enormous side-pressure.

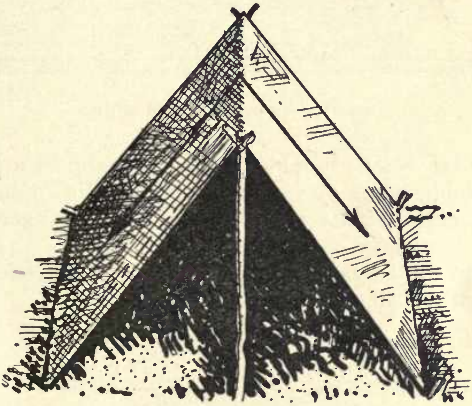


Fig. 66.—Tent-fly on ridge-pole, illustrating strike of strata.

It must always be remembered that although rocks are so hard and resistant, they can be crumpled up and corrugated like a thin sheet of iron when sufficient lateral pressure is exerted on them.

The mechanics of the folding of strata can be illustrated in a graphic manner by the following simple experiment :—

Take fifty strips of cloth of different colours, about 2 feet long and 6 inches wide, and pile them one over another on a flat table (fig. 67). The strips of cloth represent a series or succession of horizontal strata.

Next place a board on top of the pile and apply vertical pressure on the board. It will be observed that the horizontal position of the layers is not disturbed.

Suppose, however, that we now place two light weights on the board, and, holding a small piece of cardboard in each hand, apply pressure on the *ends* of the layers, slowly bringing our hands towards each other under the board. The cloth will now be found to be puckered up into a number of folds of various form and size. Moreover, the distance between the ends will be greatly reduced.

In this experiment we have a good example of what takes place when horizontal strata are folded. The lateral pressure throws the strata into folds, some of which may be gentle undulations, and others sharp corrugations according to the force exerted and the character of the rocks.

Fig. 67.—Showing pile of cloth.

It is important to note that the strata when folded cover a smaller area than when lying horizontal.

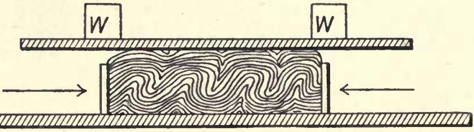


Fig. 68.—Showing pile of cloth folded by lateral pressure.

In strata that have been deeply involved in folds it is not unusual to find the contained fossils and pebbles deformed, elongated, and even sheared in the direction of the lateral movement, which is sometimes called *lateral thrust*.

The folding and crumpling of strata are generally believed to be due to lateral pressure arising from the sinking of crustal segments upon the cooling and contracting interior.

Thus, when a block of horizontal strata is squeezed into a smaller segment the effect is to crumple the strata into folds.

The arch of a fold is termed an *anticline*,[1] and the trough a *syncline*.[2]

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[1] Gr. *anti* = opposite, and *klino* = I incline.

[2] Gr. *syn* = together, and *klino* = I incline.

In a sheet of corrugated iron the ridges will represent *anticlines*, and the troughs *synclines*.

The line running along the crest of a ridge is called the axis of the ridge, *i.e.* the *anticlinal axis*, and the line along the bottom of a trough the *synclinal axis*. For example, the ridge of a tent-fly supported by a ridge-pole is the axis of the roof.

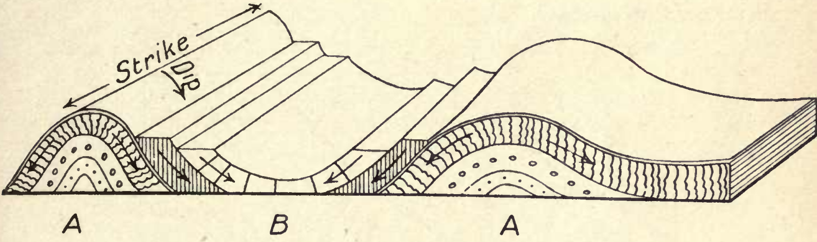

FIG. 69.—Showing folded strata.

A, Anticlines. B, Syncline.

The sides of an anticline or of a syncline are called the *limbs*. In an anticline we speak of *arch-limbs* because they form the arch; and in a syncline, of *trough-limbs* because they slope down so as to form a trough.

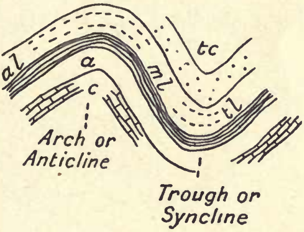

FIG. 70.—Diagram showing parts of a fold. (After Lapworth.)

(*ac*) Core of anticline. (*al*) Arch-limb.
(*tc*) Trough-core. (*tl*) Trough-limb.
(*ml*) Middle limb.

It is obvious that in the case of a syncline following an anticline, the adjacent limb will belong to both, and is therefore called the middle limb, as shown in fig. 70.

Different Forms of Folds.—According to the character of the strata and the amount of compression, folds may assume different forms. The corrugations on a sheet of corrugated iron are *symmetrical*, but symmetrical folding is not very common in Nature. More frequently one side or limb of a fold is steeper than the other, and as this is the common type of fold, it is called *normal folding*.

In fig. 71 we have a series of beds, including a seam of coal arranged in two anticlines and two synclines, the folding being normal.

In cases of sharp folding, one limb may be vertical or actually pushed over beyond the vertical. A turned-over fold is called an *overfold* or *inverted fold*.

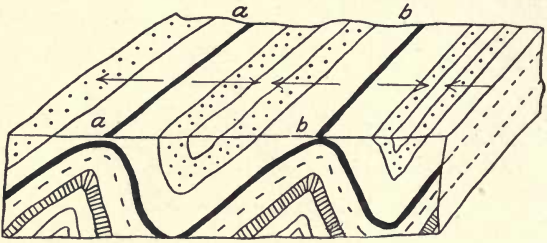

FIG. 71.—Showing folded strata in cross-section and plan.

When an overturned fold is pushed over so far that the limbs are parallel and nearly horizontal, we have what is termed a *recumbent fold*.

In what is termed a *monoclinal fold*, the strata are bent from the normal direction for a distance and then resume the original plane. In sharply bent monoclinals, the strata in the middle limb are generally drawn out, compressed, or deformed.

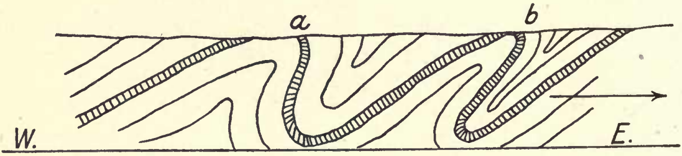

FIG. 72.—Section showing fold with vertical limb *a*, and overfold at *b*.

A notable example of monoclinal folding is seen in the Isle of Wight where, on the south side of the island, the Cretaceous rocks are tilted till they are almost vertical, while the Lower Tertiary strata follow with a similar inclination, but rapidly flatten down, going northwards till they become horizontal on the north coast.

A succession of closed overturned folds forms what is termed an *isoclinal*. Folds of this type are frequently met with among the older schists and gneisses, and sometimes among Mesozoic rocks.

Strata that have been uplifted in the form of a *dome* so as to incline outwards in all directions, are said to have a *qua-qua-versal* dip.

FIG. 73.—Showing *monoclinal* folding of Lower Tertiary strata in section of the Isle of Wight, Totland Bay to Headon Hill. (After H. W. Bristow.)

a. Chalk.—Cretaceous.
b. Reading Beds.
c. London Clay.
d. Lower Bagshot Beds.
e. Bracklesham Beds.
f. Barton Clay.
g. Barton Sand.
} Eocene.

h. Headon Beds.
i. Osborne Beds.
k. Bembridge and Hamstead Beds.
} Oligocene.
m. Gravels.—Recent.

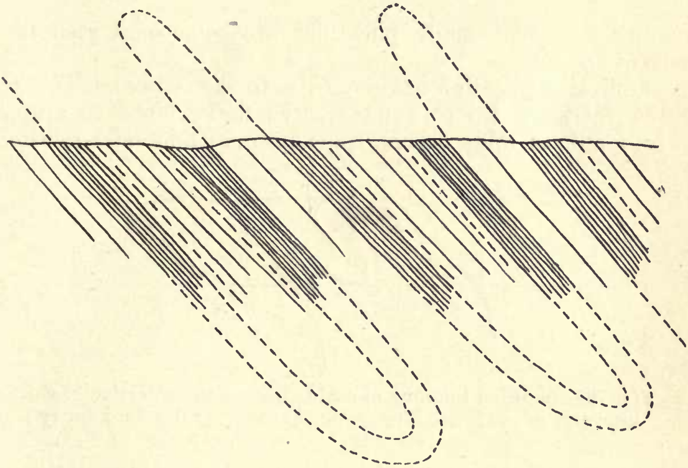

FIG. 74.—Showing *isoclinal* or *closed* folds.

Great arches or great troughs with minor corrugations on their flanks are termed *geanticlinals* (or *anticlinoria*) and *geosynclinals* (or *synclinoria*) respectively.

In the central massif of the Alps, the strata are arranged in a singular radial form, with great flanking corrugations. This is termed *fan-folding*, of the Alpine type.

Radial folding on a minor scale is sometimes seen in volcanic regions, arising from rapid local subsidence accompanied by lateral pressure.

Plication of Strata.—Plication is merely a form of minute folding. It is frequently seen among gneisses, mica-schist, and other metamorphic rocks that have been subjected to enormous lateral pressure. A great many plications are sometimes seen in the space of an inch.

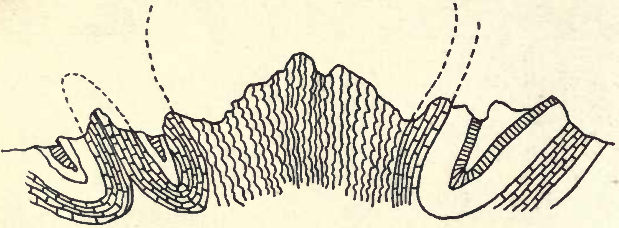

Fig. 75.—Showing example of fan-folding in *European Alps*. (After Heim.)

Complicated plication has given rise to the term *contorted*, which is frequently applied to banded rocks that have been crumpled up into minute folds. Thus some gneisses and mica-schists are spoken of as *highly contorted*, which usually means that the rocks are finely plicated.

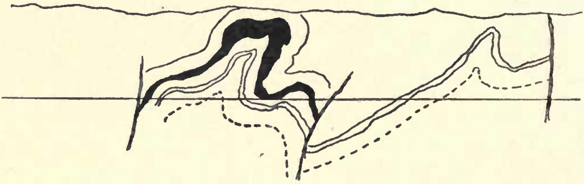

Fig. 76.—Showing thinning of coal-seam due to contortion of coal-measures in the Saint Eloy Basin, France. (After De Launay.)

The hardest and most resistant rocks, under the influence of great stress, behave as semi-plastic bodies. In the process of folding, the limbs of the plications are frequently found to have been squeezed until they have become thin. Where this has happened, the crests and troughs of the folds usually show a corresponding thickening, the flowage being from the region of greatest stress in the limbs to the places of least stress in the arches and troughs. The hardest mineral substances, even quartz, seem to be capable of flowage under the influence of sufficient pressure.

Shales, sandstones, and nearly all sedimentary rocks exhibit the same thinning in the limbs of sharp folds due (*a*) to compression and consolidation of the constituents, or (*b*) to the elongation arising from the shearing which has so frequently accompanied sharp folding and crumpling of the strata.

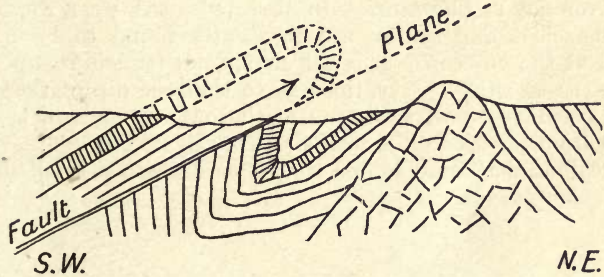

Fig. 77.—Showing effect of overthrust folding.

Overthrust and Shearing.—When an overturned fold is thrust against a boss of granite or a mass of any hard resistant rock, the lateral pressure may cause the fold to override the strata lying against the resistant boss. In this way rocks may be gathered up in great earth-folds and pushed for many miles from the place where they were originally formed. Notable examples of overthrust are found in the Alps and in the Highlands of Scotland.

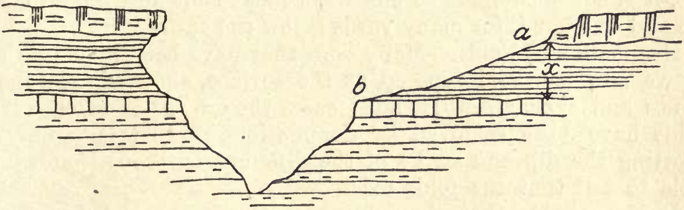

Fig. 78.—Showing outcrop of horizontal strata in a gorge.

When the force exerted in the folding exceeds the elastic limit of the rock, rupture takes place usually in the apex of the fold, followed by shearing and acute faulting.

Outcrop.—The edges of strata which appear at the surface are called the *outcrop*. The exposed edges of hard resistant rocks sometimes form conspicuous escarpments that can be traced for many miles.

When the strata are horizontal, the outcrop of the different beds will only be seen in a sea-cliff, valley, or gorge.

On sloping ground the extent of the outcrop does not represent the true thickness of the beds. For example, in fig. 78 the thickness of the bed lying between the two bands of limestone is not *a–b*, but the line *x* at right angles to the plane of the bed.

Outcrop Sag or Curvature.—In dissected areas, weak rocks, such as mica-schist and shales, are frequently found to be bent or curved at the outcrop. This sag sometimes renders it difficult to obtain trustworthy observations as to the true dip of the strata. It is caused by the drag or sag of the outcrop ends of the beds arising from the stress due to their own weight (fig. 79).

In regions that were at one time covered with a thick sheet of ice, it is not uncommon to find weak rocks bent, or even crumpled up and shattered, for many yards below the surface.

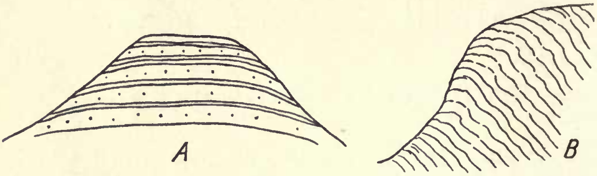

FIG. 79.—Showing effects of outcrop sag of strata.
A, In horizontal beds. B, In tilted beds.

Denudation of Folds.—Many beds that have been folded do not, as we now see them exposed at the surface, show complete anticlines and synclines. In most cases the crowns or crests of the folds have been removed by denudation, so that it is only by plotting the dip and strike of the different outcrops that we are able to tell that the folds exist.

It is probable that the folding of the strata and denudation proceeded at the same time. In this case the crown of the fold would be worn away in such a manner that the complete arch, as indicated by the dotted lines in fig. 80, probably never existed.

It is not often that the apex of an anticline is seen, except in the case of small folds.

Strata arranged in the form of an anticline will be worn away faster than the same beds disposed in the form of a syncline. In the anticlinal arrangement the limbs dip away from each other, which permits the rain to find its way readily along the bedding planes, where it disintegrates the rock, thereby assisting the force of gravity in breaking up the outcrops. The rain-water lying between the bedding planes by its hydraulic pressure also exerts a strong disruptive force which, in cold climates, will receive effective help from frost.

In the case of the synclinal arrangement, the limbs dip towards one another, the different beds resting on each other like a pile of saucers. The beds thus support one another, and consequently their exposed edges alone are subject to the effects of denudation.

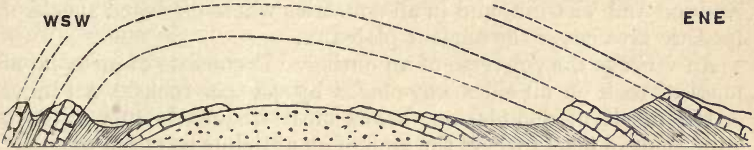

FIG. 80.—Showing denuded crown of anticlinal fold of Silurian rocks in the Valley of Woolhope, Herefordshire.

Hence, we frequently find that the valleys have been excavated along the course or axis of anticlines, while in the adjacent ridges the beds are arranged in synclinal folds as shown in fig. 81.

Outliers and Inliers.—These commonly arise from the denudation of horizontal or gently undulating strata. Many formations that at one time formed a continuous sheet over extensive areas

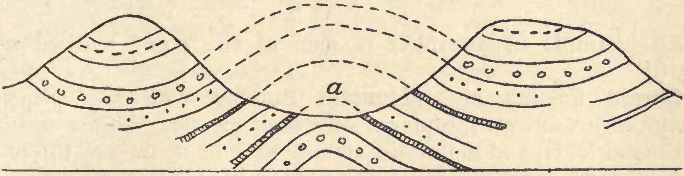

FIG. 81.—Showing valley excavated along course of an anticline, and ridges composed of beds arranged in synclinal folds.

have been greatly reduced in size, and in some cases they are now represented by only a few interrupted sheets and isolated patches.

A notable example of the gradual destruction of a formation is exhibited by the *Desert Sandstone* which at one time covered over 400,000 square miles of the surface of Queensland, but has now been worn away to about a twentieth of its former extent, and is represented only as a series of isolated ridges, peaks, plateaux, and *mesas*[1] scattered over the interior.

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[1] Span. *Mesa* = a table.

An *outlier* is simply an isolated remnant of more extensive beds, and is usually defined as a detached mass of rock *surrounded* on all sides by *older* rock.

Outliers occur among all kinds of rock, including loose gravel. The beds forming them may be horizontal, inclined, or folded. Examples are frequently met with in front of prominent escarpments of limestone and basalt.

Outliers of Jurassic and Cretaceous strata are common in Central England. Table-topped outliers of basalt are numerous in New Zealand and Victoria, and in all countries where dissected sheets of basaltic lava cover the ancient plateaux.

An *inlier* is the converse of an outlier. It consists of an isolated mass of rock on all sides *surrounded* by *younger* rocks. An inlier is the result of denudation, hence most frequently met with in valleys, or in places where the arch of an anticline has been partially worn away.

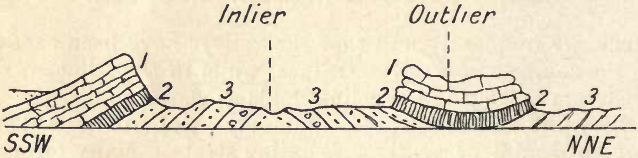

Fig. 82.—Section along west side of Weka Pass, N.Z., showing outlier.
(1) Weka Pass stone. (2) Amuri limestone. (3) Greensands.

An example of an inlier is seen at the point marked *a* in fig. 81.

Crustal Folding and Mountain Building.—All the principal mountain chains on the planet owe their existence to the uprising of crustal folds, and mountain-making may be defined as the result of localised folding in regions where the uplift is faster than the rate of denudation. If the rate of denudation were equal to the rate of uplift, it is obvious that the truncated and dissected folds would never form highlands or features of bold relief. A potential mountain-making fold suppressed by denudation would in time become buried in the waste derived from its own destruction, and the ultimate result would be a worn-down stump indistinguishable from the stump of an alpine chain worn down by long-continued subaerial denudation.

Alpine chains may therefore be regarded as the expression of relatively rapid folding.

It is seldom that a mountain chain consists of a simple synclinal fold. More often the great chains consist of a series of deeply dissected isoclinal folds forming a confused alpine complex, flanked by many more or less parallel ranges. The great height and rugged contours of the Pyrenees, Alps, Himalayas, Andes, and Rocky Mountains are an evidence of their comparative youth. Their uplift has been so recent and rapid, that denudation has merely succeeded in eroding the crests of the folds into narrow serrated ridges, deep valleys, and profound gorges.

There is evidence that great alpine chains existed in the remotest geological ages. All of these chains were vigorously attacked by the contemporary agents of denudation, their waste furnishing the sediments that built up the later formations. The only vestige that remains of these primitive alps is their worn-down stumps, many of which have lain for countless æons buried beneath piles of sedimentary strata. Here and there the buried stumps have become exposed by recent denudation, or disclosed by deep boring.

When a renaissance of the folding movements takes place along the segment occupied by a worn-down and buried alpine chain, a second alpine chain may rise on the ruins of the first. Most of the existing mountain chains occupy the ruins of Palæozoic chains, the stumps of which have sometimes become involved in the later folds.

In the complex structure of Europe, Lapworth and Suwess have recognised three primary folded chains all overfolded towards the north, namely :—

(1) The Caledonian, S.W.–N.E.—Pre-Devonian.
(2) The Armorican, W.N.W.–E.S.E.—Pre-Permian.
(3) The Variscan, W.S.W.–E.N.E.,—Pre-Pliocene.

The Caledonian is the northernmost of these ancient alpine chains. It is composed of a massif of Archæan granites, gneisses, schists, and older Palæozoic slates, sandstones, and quartzites that extend from the west of Scotland north-eastward to the northern limits of Scandinavia. It causes little surprise to find that rocks of such antiquity have been crushed into many complex folds, overthrust, and profoundly faulted.

The Armorican folded chain, so named from the ancient name of Brittany, is the result of movements that ridged up the Devonian and older Carboniferous formations between the close of the Early Carboniferous and the advent of the Permian. The truncated remains of this western alpine chain can still be traced from Ireland to Central France, buried beneath a pile of Mesozoic and younger formations.

The Variscan or eastern fold is of Cainozoic date. It extends from the Atlantic border through Southern France to Northern Bohemia, and includes the Pyrenees, Alps, and Carpathians.

In Asia, the Caucasus, Hindu Kusch, Altai, Thian Shan, and

Himalaya Mountains are composed of folds of the Variscan type, the axes of which lie approximately parallel with the Equator.

The great Ural chain consists of folds running north and south.

In the American continents, the Pacific Ocean is bordered by high mountain chains that are surmounted by many active and extinct volcanoes. These are typical folded chains of the meridional type, but turn their folds towards the abysses of the sea. The segment of the Aleutian Islands forms an independent fold.

It is significant that all the great chains of Europe, Asia, and North Africa, with the exception of the Urals, are composed of east and west folds; while the Andes, Rocky Mountains, and Sierras in America run parallel with arcs of the meridian.

Volcanic activity is frequently associated with areas of vertical displacement resulting from faulting or intense folding; and all great earthquakes are the jolts propagated by the revival of movement along ancient, but in most cases well-defined fault-lines.

SUMMARY.

Elevation.—(1) The occurrence of rocks containing marine shells at a height above sea-level is an evidence of elevation of the land in past geological times. The existence of raised-beaches or sea-strands is a proof of comparatively recent elevation.

Subsidence.—(2) The best proofs of subsidence are submerged forests and coal-seams, drowned valleys, and atolls.

The forests grew on the dry land near the sea, and could only become submerged by the sinking of the coastal region. Likewise coal-seams are composed of the remains of a terrestrial vegetation that required air and sunlight for its growth. Therefore, when seams are found thousands of feet below sea-level, we know that subsidence to that extent has taken place.

The fiords of Norway and New Zealand are merely submerged mountain-valleys. In California and elsewhere some of the existing river-valleys can be traced by soundings far seaward of the present shore-line—clearly a proof of subsidence in quite recent times.

According to the view of Darwin, atolls and barrier reefs were formed by the upward growth of the coral-building polyp on a slowly sinking sea-floor. The borings at Funafuti showed the existence of coralline and foraminiferal limestones at a depth of 1114 feet below sea-level; and since the coral polyp cannot live in water deeper than say 150 feet, a subsidence of over 900 feet must have taken place in that area.

As the land sinks below the sea, the coral reefs grow upward, and their distance from the shore-line increases until in the case of a continent or large island a barrier reef is formed, and in the case of a small island an encircling reef. When the land encircled by a coral reef finally disappears below the surface of the sea, an *atoll* is formed.

(3) Rapid earth-movement may be due to volcanic eruptions or to the sudden jolts arising from earthquakes.

Tilting of Strata.—(4) The direction in which a stratum or bed is inclined is called the *dip*; and the amount of the inclination measured from the plane of the horizon is the *angle of dip*.

The *strike* is the horizontal line along the tilted stratum, and it is always at right angles to the dip.

Folding of Strata.—(5) The majority of sedimentary or aqueous rocks were laid down in a horizontal position, but many of them have since been pushed into folds by lateral pressure that in all probability arose from the cooling and contracting of the Earth's crust.

The arches of folds are called *anticlines*, and the troughs, *synclines*. Simple symmetrical folding is rare. More commonly the folds are unsymmetrical, the limbs being shorter and steeper on one side than on the other.

Folds that have been subjected to great lateral pressure from one direction are sometimes pushed over and form what are called *overturned* or *inverted* folds. When an overturned fold is pushed over until the limbs are closed and nearly horizontal, it is called a *recumbent* fold.

A succession of closed folds that are overturned, but not recumbent, form an *isoclinal*.

Great anticlinal arches with minor corrugations on the flanks are called *geanticlinals*, and great troughs, *geosynclinals*. In the Alps of Switzerland, Heim has identified what is thought to be a *fan* or *radial* form of folding.

Plication of Strata.—(6) Plication is a form of minute folding frequently seen among the older altered rocks, such as gneiss and mica-schist. Plication may be very complicated. Rocks that are strongly plicated are frequently spoken of as *contorted*. Contorted schists sometimes exhibit a thinning or drawing out of the limbs of the folds with a corresponding increase in the arches and troughs. This indicates that a certain flowage of the rock-constituents took place under the stress of enormous pressure. In other words, under great pressure the rock-constituents behave as plastic bodies.

Shearing.—(7) When rocks are subjected to a travelling lateral pressure that is arrested by some massif of hard resistant rock, such as a granite-boss, they are frequently forced into sharp overturned folds which may become fractured and sheared, the upper portion of the fold being pushed over the lower. This *overthrusting* of crustal segments has been observed in the Alps by Heim, and in the Highlands of Scotland by Peach.

Outcrop.—(8) The edges of strata that appear at the surface are called the *outcrop*. Weak rocks may be bent or curved at the outcrop by the weight of their own mass or by the stress of a sheet of moving ice. Such *outcrop curvature*, as it is called, is common in shales, phyllite, and mica-schist.

Denudation of Folds.—(9) The majority of folds of considerable size have been denuded to a greater or less extent; hence their existence is generally deduced by construction from the observed dips and strikes as recorded in the field.

(10) *Outliers* are the isolated remnants of a rock-formation that at one time formed a continuous sheet over an extensive area. They may be defined as detached masses of rock surrounded on all sides by older rock.

An *inlier* is the converse of an outlier. It consists of an isolated patch of rock surrounded on all sides by younger rock. Hence inliers are most frequently found in the exposed crowns of anticlines.

Crustal Folding and Mountain Building.—(11) Mountain chains are composed of great uplifted crustal folds that have been deeply dissected during the progress of the uplift.

CHAPTER X.

JOINTS, FAULTS, CLEAVAGE.

Joints.

Joint Structure.—Joints are simple cracks or fissures. They are found in rocks of all kinds and of all ages.

Sedimentary rocks are usually traversed by two systems or sets of joints, both perpendicular to the stratification planes, and commonly intersecting one another at right angles. The joints in each set are approximately parallel to one another.

As a rule, one set of joints is more pronounced than the other, and may be traced for many yards. The joints in the major set are commonly called *master-joints*.

The course of the master-joints is usually parallel with the strike of the main lines of uplift; that is, parallel with the axes of the anticlines.

The two sets of joints and the bedding planes give three planes nearly at right angles, which divide the rock into cuboidal or prismatic blocks and columns.

Rocks that have been much disturbed are sometimes intersected with three or four systems of joints. Generally speaking, rigid rock is more jointed than one that is more yielding.

The joints in each set may be many feet or yards apart, or in exceptional cases only an inch or less.

In horizontal strata, the joints are usually approximately vertical; but in regions where the rocks have been subject to great disturbance, the joint planes may occupy any position.

Joints are sometimes mistaken for bedding planes, but these can usually be distinguished by lines of material of different texture or colour, or by lines of nodules and hard bands.

Joints are of necessity confined to the zone of fracture; and in the majority of cases, an individual joint when followed along its course seems to die out in less than a score of yards, to be succeeded after a longer or shorter interval by another joint following the same general direction.

Many joints end at the contact of two kinds of rock, but *master-*

joints may pass through a whole series of rocks. For example, throughout the whole of Yorkshire the Mountain Limestone Series is traversed by master-joints passing downward through the limestone, sandstone, and shale in nearly the same direction.

Joints are more or less open, or usually filled with silt and mud carried into them by water. In many cases, more especially in limestones and other calcareous rocks, they have been enlarged into gaping fissures or caves by the action of underground waters. On the surface they frequently become enlarged through the solvent effect of rain, aided by the ordinary processes of weathering.

Joint planes sometimes show polished and grooved surfaces, which would tend to show that a certain amount of sliding movement had taken place parallel to the polished faces. Evidence of displacement along joint planes is perhaps exceptional.

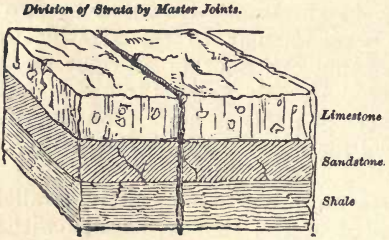

Fig. 83.—Showing master-joints passing through different rocks.

The majority of the older coal-seams are traversed by two sets of vertical joints called *cleats*, crossing one another at right angles. The *face cleats* run parallel with the strike of the seam and are usually the more pronounced. The *end* or *butt cleats* are shorter and not as a rule so well defined.

The *cleats* are of great importance in facilitating the getting of the coal; hence the direction of the working faces or breasts with reference to the *cleats* is a matter of supreme importance.

The joints in igneous rocks are not generally so regular or well defined as in sedimentaries. But in exceptional cases they are so symmetrically disposed as to produce the well-known prismatic columnar structure which is sometimes seen in flows of basaltic rock, and less often in andesites and rhyolites.

Granite is frequently intersected with two sets of joints, one of which is sometimes well defined. When the joints are far apart, large blocks of stone can be obtained, but when they are close together, the rock is broken up into a rubble of small fragments (Plate XIII.).

The master-joints, in whatever rock they occur, are always utilised by the workmen to facilitate the hewing of the stone in blocks that can be turned to commercial account.

Causes of Jointing.—The mechanics of jointing has not yet been satisfactorily explained, although many suggestions have been advanced by different writers. The generally accepted opinion is that the joint-cracks are the result of the various stresses connected with the contraction and folding of rock-masses.

Among the stresses referred to are *shrinkage* arising from the drying, or cooling of the rock, *tension* and *shearing* due to folding.

Thick sheets of mud when drying in the sun develop vertical cracks due to the dehydration and contraction of the mass. Sheets of lava in the portions exposed to the cooling effects of the atmosphere or of the surface on which they rest, as they cool also develop well-defined cracks that only in exceptional cases show the symmetrical arrangement known as columnar structure.

In sedimentary rocks the *master-joints* may pass downward through different kinds of rock; and in passing through a conglomerate may even sever the constituent pebbles in two. Clearly then the jointage in these cases took place after the consolidation of the rocks.

The orientation or general direction of the *master-joints* in clastic rocks is usually parallel with the axes of the folds, which would lead us to the conclusion that it was in some way genetically connected with the processes or mechanics of folding. It would seem as if the stresses arising from the bending of the hardened and rigid rock-mass were relieved by the formation of innumerable short cracks or rents running parallel with the main line of uplift; that is, parallel with the strike. In other words, when the bending exceeded the elastic limit of the rock, parallel fractures would be formed.

But anticlinal folds have a beginning and an end. Some may be short and plunge steeply at the ends. Others may extend for scores or even hundreds of miles before they die out.

The formation of an anticlinal fold can be best understood by reference to a simple experiment. Suppose, for example, that we place a long pillow or bolster lengthwise on a table and over it throw a sheet or table-cloth.

It will at once be seen that the anticline of cloth rises gradually from one end of the table until it becomes well defined along the body of the pillow; and at the other end plunges or *pitches*, as it is called, until it finally dies out as the horizontal surface of the table is reached.

By a similar experiment with two pillows and a sheet it can be shown that synclines also have a beginning and an end.

Let us now suppose that the table-cloth is replaced with a sheet of hardened rock bent into a simple fold. It is obvious that the greatest bending stress will be exerted parallel to the axis of the anticlinal uplift. If the rock is rigid and refuses to bend easily, the stress will be relieved by the formation of *master-joints* running parallel with the strike or axis of the fold. These joints will be *tension-cracks*, developed in the tension-zone.

There will also be a tensional stress at the ends of the folds due to the extension of the strata as it rises from the horizontal position. This stress will not be so great as that parallel with the axis, and as a consequence it will be relieved by the formation of smaller and shorter joints.

Joints formed by anticlinal folding are obviously the result of tension in the *upper* layers of the uplifted mass; while those arising from synclinal folding are the result of tension in the *lower* layers, in accordance with a well-known law in mechanics.

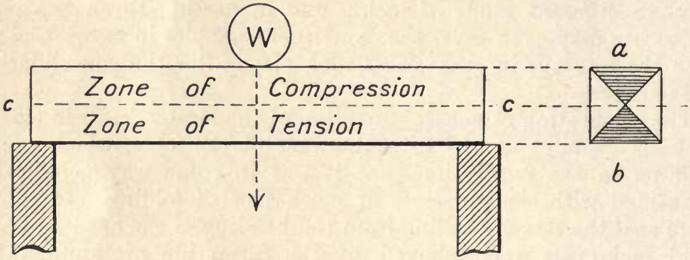

FIG. 84.—Showing distribution of stresses in a loaded beam.

For example, if we take a beam of wood, supported at both ends and loaded at the centre, the upper layers will be in compression and the lower in tension, as shown in fig. 84.

The portion of the beam lying above the *neutral axis* or line of no stress, *c c*, will be in *compression*, and the portion below the neutral axis in *tension*. The magnitude of the stresses is greatest at the upper and lower surfaces of the beam, and diminishes as the neutral axis is approached, as graphically shown by the shaded portions of the stress diagram at *a* and *b* (fig. 84).

If the force were applied from below so as to cause upward bending, or a tendency to bend, the upper layers would obviously be in tension and the lower in compression.

Now, bending in any direction is always accompanied by a *horizontal shearing stress*, although in a homogeneous beam or mass this stress is not always obvious. But its existence can easily be proved experimentally.

If we replace the solid beam with a pile of thin boards, supported at both ends and loaded with a weight W at the centre, the boards will not only be bent, but they will also slide over one another as a result of the horizontal shearing stress, as shown in fig. 85.

Stratified rocks that have been sharply folded frequently exhibit evidence that slipping or shearing has taken place along the bedding planes during the process of folding. The presence of a layer of clay, as well as grooves and striæ on the bedding-plane surfaces, are among the most obvious of these evidences. In cases where the shearing stress cannot be relieved by the movement of the beds, relief may be found by the formation of joints or cracks at right angles to the line of force.

The jointing of rocks may, therefore, be set down mainly to the influence of tension and shearing resulting from crustal disturbance, sometimes supplemented by the stresses introduced into rock-masses by shrinkage during the processes of drying and cooling.

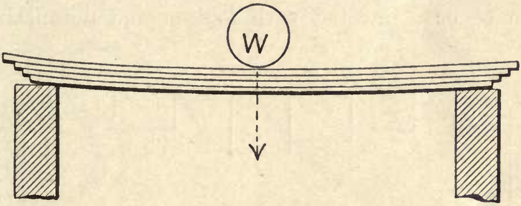

Fig. 85.—Showing effect of a horizontal shearing stress.

Faults.

A crack or rent without movement of the rock on either wall is a simple fracture. In the majority of large cracks there has not only been fracture, but also displacement. In other words, the rents have become what are known to geologists and miners as *faults*.

Definition of Fault.—A fault may be defined as a fracture, on one side of which movement has taken place, whereby the rocks on that side have been displaced relatively to those on the other side.

Origin of Faults.—Faults are caused by crustal stresses arising from the slow secular folding movements that build up mountain-chains, or from the sharper movements propagated by the intrusion of igneous magmas or by earthquakes. That is, the disturbing agents may be *orogenic* or *hypogenic*.[1]

A fault may be the result of a single continuous movement, slow or fast, or of a succession of slight movements, with intervals of quiescence. The renaissance of movement on an ancient fault-

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[1] Gr. *hypo* = under, and *genesis* = production.

plane may be responsible for the production of earthquakes and other seismic phenomena.

In regions where the rocks have not undergone much disturbance, but approximately occupy the original position in which they were laid down, the faults are probably due to mere subsidence of crustal blocks, arising from the action of *vertical shearing stress.* In a loaded beam this stress tends to fracture the beam in a vertical direction, and in every crustal segment there must be the same tendency. When the stress exceeds the ultimate strength of the rocks composing the segment, fractures will be formed, producing the effect known as step-faulting, shown in fig. 100.

Coal-mining operations have shown that the coal-measures in most lands are intersected by numerous faults, and it is probable that all portions of the Earth's crust are dislocated in the same way.

Many, if not the majority, of the great faults that traverse the crust seem to be connected with folding and mountain-building. They are frequently zones of dislocation or thrust-planes rather than true faults.

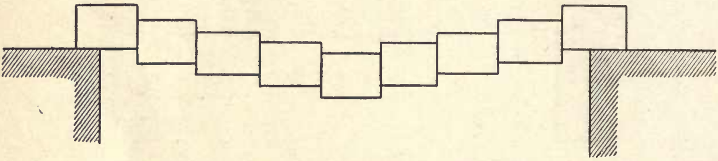

FIG. 85A.—Showing effect of vertical shear.

The inclination of faults, measured from the horizon, is generally high, being in most cases over 40°. The inclination of thrust-planes, on the other hand, is, as a rule, quite low, seldom exceeding an angle of 20°. This seems to be a consequence of their origin, for it is only when the folds have been thrust into a nearly recumbent position that fracture and shearing take place.

Relationship of Faults and Joints.—Joints may be taken as the expression of the internal stresses arising in disturbed rock masses ; and faults as the expression of the rupture by which crustal folds achieve relief when the stress exceeds the limit of relief afforded by joints.

Therefore, while joints and faults are essentially different, they can both be traced to the same cause, and in this respect they may be said to have a close genetic relationship.

Relationship of Faults and Folding.—The stress of sharp folding is frequently relieved by the formation of powerful fractures which by movement or shearing may develop into faults. In fig. 86 we have an example of folding without fracture, and of folding with fracture, accompanied by *shearing*, resulting in the formation of a *shear-plane* or fault. An example of overthrust folding, followed by fracturing and faulting of the folded rocks, is shown in fig. 77.

Linear Extent of Faults.—Faults, like joints, have a beginning and an end. They begin gradually, attain a maximum, and then gradually die out. Many of the small faults met with in mining regions are short, frequently less than a hundred yards long. Some large faults, however, can be traced for scores of miles. Such great dislocations should perhaps be best described as thrust-planes rather than mere faults.

The course of large faults is usually more or less sinuous, and some fault-faces exhibit many minor corrugations.

Evidences of Faulting.—The opposing walls or surfaces of a fault-plane are generally polished, scratched, and grooved by the rubbing which took place when they moved against one another. Such polished and striated surfaces are called *slickensides*.

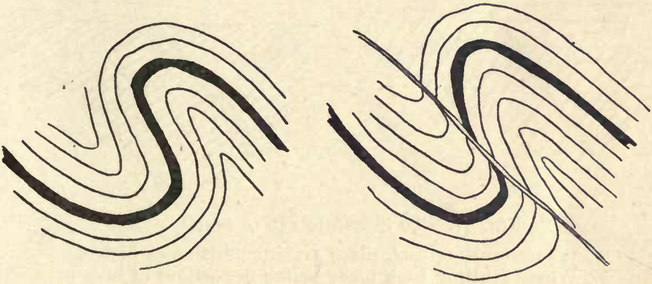

FIG. 86.—Showing effects of folding and fracture accompanied by faulting.

In many cases the fault-fissure is filled with crushed rock fragments, or lined with a layer of clay which is known to miners as *pug*. This clay is merely rock-flour, and it may be soft, or so hard as to resemble a slaty shale.

In powerful faults in which great movement has taken place, the wall-rock may be crushed and *brecciated*—that is, broken into angular fragments—for a width of many yards. For example, the plane of the Moanataiari fault which intersects the Thames Goldfield in New Zealand is in places occupied by a zone of crushed rock and soft clay, varying from 40 to 100 feet wide.

Many fault-fractures became channels for the circulation of mineralised waters, which deposited in them quartz or other crystalline minerals together with ores of great economic value.

It was in this way that many of the most valuable ore-veins were formed.

Age of Faults.—A fault is obviously younger than the rocks which it intersects, and when the rocks are traversed by two systems of faults, one system will generally be found to displace the other, thereby affording conclusive evidence that it is the younger.

A fault that traverses, for example, a pile of Cretaceous and Miocene strata must be younger than Miocene. If the Miocene beds are overlain by Glacial Drift which is not disturbed by the fault, then the date of faulting took place some time *after* the Miocene, and *before* the advent of the Glacial Period.

Or again, if the fault traverses the Cretaceous beds and not the overlying Miocene, as in fig. 87, B, then we know that the fault is younger than Cretaceous, but older than Miocene.

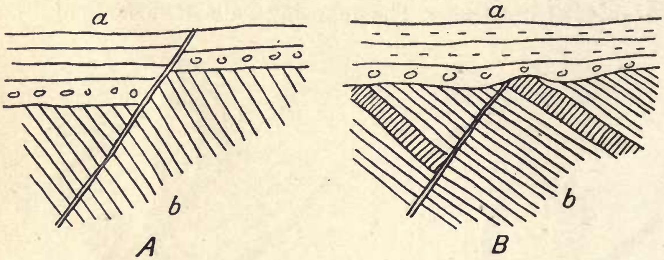

Fig. 87.—To illustrate age of faults.

A, Where faulting took place after deposition of beds *a*.
B, Where faulting took place before deposition of beds *a*.
(*a*) Miocene beds. (*b*) Cretaceous beds.

Movement is believed to be still in progress along the planes of some of the great faults of late Tertiary date. The joltings caused by the sudden settlement of the ground on the downthrow side of the San Juan fault are held by some to have been responsible for the disastrous earthquakes that ruined San Francisco in 1906.

Fault-Structure.—Faults intersect rocks of all kinds and all ages. Some of them are crustal dislocations of great magnitude that can be traced on the surface for scores and even hundreds of miles.

Faults may run in any direction, but the major faults of a region frequently possess the same general bearing.

A fault may run parallel with the strike of a bed or lode, or it may cross the strike at right angles or at any other angle.

Some regions are intersected by a number of parallel faults, and in some places two or more independent systems of faults may mutually intersect one another.

Hade of Faults.—Faults are not often vertical, but generally incline to one side or the other. A fault is said to *hade* when it inclines from the vertical plane. The *hade* of a fault is, therefore, the angle which the fault makes with the vertical plane. *Hade* and angle of *dip* are thus only the same when both are 45°.

The hade-line of a fault is the resultant of two principal component forces, namely, gravitational stress acting vertically towards the centre of the Earth, and lateral thrust mainly due to subsidence.

Classification of Faults.—Faults, according to the direction of the vertical displacement, are divided into two classes, namely:—

(*a*) *Normal faults.*
(*b*) *Reversed or overlap faults.*

In *normal faults* the *downthrow* of the beds or lode is towards the side to which the fault inclines or hades. Thus, in fig. 88 the hade and downthrow are both in the same direction. This is the most common type of fault; hence the name *normal.*

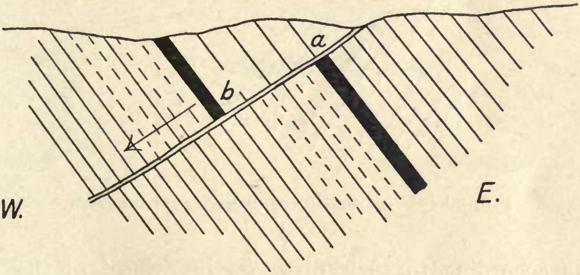

Fig. 88.—Cross-section showing direction of downthrow in normal fault.

Here the seam of coal has been faulted down from *a* to *b* in the direction indicated by the arrow.

In reversed or overlap faults the downthrow of the beds is on the under or *foot-wall* side of the fracture, as shown in fig. 89.

In the above figure the hade is towards the west, but the downthrow is on the under or foot-wall side. That is, the seam has been displaced from *b* to *a*; or if we assume that *a* is the original position of the seam, then it has been moved from *a* to *b*; that is, contrary to the direction of the hade.

In fig. 77 we have an example of fracturing and faulting in the middle limb of an overturned fold arising from the resistance of the granite boss to the lateral thrust from the south-west.

Displacements caused by Faults.—Faults cause different effects according to the direction of their strike and dip relatively to the strike and dip of the beds, seam, or lode which they intersect.

A fault which runs parallel with the strike of the beds is termed a *strike-fault.* It may dip with the bed or against it.

A fault which runs in the same direction as the dip of the beds—that is, at right angles to their strike—is called a *dip-fault.* A fault, however, may pursue any course between the strike and dip of a bed; consequently the distinction between strike-faults and dip-faults is sometimes not very well marked. For example, when the course of the fault is midway between the dip and strike of the bed, the fault may be termed either a dip-fault or a strike-fault.

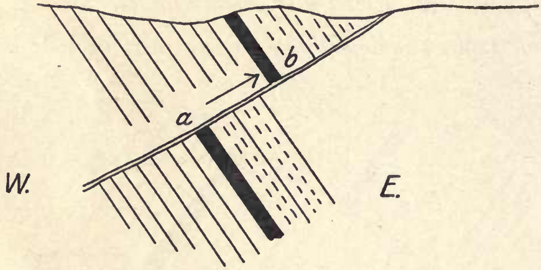

FIG. 89.—Cross-section showing reversed fault.

Faults according to their direction in respect of the beds or lodes they intersect may cause :—

(1) A vertical displacement = *throw.*
(2) A horizontal displacement = *shift* of faulted bed.
(3) An *apparent* lateral displacement = *heave.*

The vertical displacement may vary from the fraction of an inch to thousands of feet. For example, the great 10-yard seam of coal in Staffordshire has been thrown down 450 feet.

The horizontal shift of the dissevered portion of a bed may amount to thousands of feet, and is dependent on the amount of *throw* and the angle of inclination of the fault-plane, as will be shown later.

The apparent lateral displacement caused by faulting is dependent on the throw and the amount of denudation the country has suffered since the faulting took place.

When a fault displaces stratified rocks, the lines of bedding afford a measure of the vertical displacement; but, in the absence of some rock marked by a distinctive peculiarity of colour or composition, there is no means of estimating the amount of disturbance.

Effects of Faults on Horizontal Strata.—When a vertical fault intersects a horizontal bed, such as a seam of coal, the only displacement is a vertical one, but inclined faults cause both vertical and horizontal displacement.

In fig. 90 a horizontal seam of coal is intersected by faults A, B, and C; A being vertical, B steeply inclined, and C relatively flat.

It is obvious that the vertical displacement or *downthrow*, commonly called *throw* by miners, equal to *m n*, is the only displacement caused by the vertical fault A. There is no horizontal displacement.

Fault B is inclined to the east, and causes a vertical displacement *d s*, and a horizontal displacement *d e*, which represents the horizontal disseverment of the ends *e* and *s*.

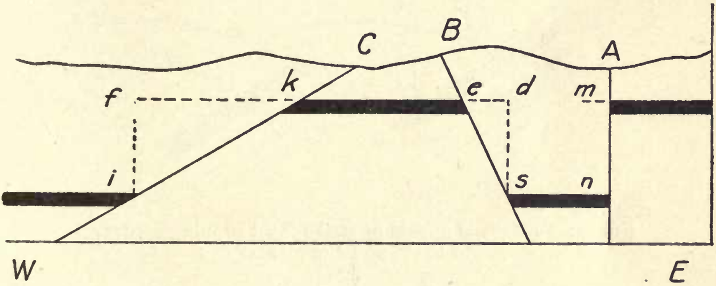

FIG. 90.—Showing effects of normal faults on a horizontal bed or seam.

Fault C produces the same amount of downthrow as fault B, but being much flatter, it causes nearly four times as much horizontal displacement; that is, $fk = 4\,ed$. It is obvious that the *flatter* the plane of the fault, the *greater* will be the horizontal displacement.

The expressions *downthrow* and *upthrow* as used by miners are merely co-relative terms applied to the vertical displacement. Thus, if the mine workings were advancing from *n* to *s*, the direction of the faulted seam *e k* would be spoken of as an *upthrow*. If, on the other hand, the direction of the workings was from *k* to *e*, then when the fault was encountered the position of the seam at *s n* would be said to be the result of a *downthrow*.

The faults A, B, C, shown in fig. 90, are examples of normal faulting.

Summarising the foregoing, we find that when an inclined fault intersects a horizontal bed or seam the displacements are :—

(*a*) A vertical downthrow (or upthrow) = *throw*.
(*b*) A horizontal disseverment due to the faulted portion sliding down the fault-plane. For the same *throw*, the flatter the fault-plane, the greater will be the horizontal shift.

Do not fail to note that no lateral displacement or *heave* has taken place in the examples of faulting shown in fig. 90, where we have only vertical downthrow with fault A, and downthrow and disseverment with faults B and C.

Effects of Strike-Faults.—A strike-fault runs parallel with the strike of the bed or seam. It may dip with the bed or against it, and according to the direction of the hade it may be a normal or reversed fault.

A strike-fault causes vertical and horizontal displacements of the beds intersected, as shown in fig. 91.

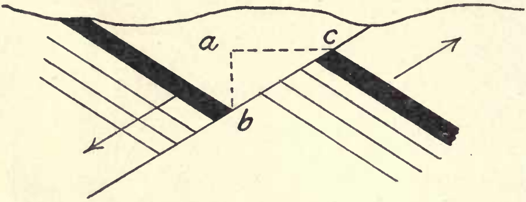

FIG. 91.—Showing effects of strike-fault dipping contrary to the dip of the strata.

In this figure the vertical downthrow = *a b*, and the horizontal shift = *a c*.

A strike-fault causes a repetition of inclined beds, as shown in fig. 92.

In regions that have suffered considerable denudation, a faulted bed or seam of coal may be partly removed on one or both sides of the fault, as shown in fig. 93.

Thrust-Planes.—Strike-faults may dip or hade in the same direction as the beds they intersect, and the angle subtended between the bedding planes and fault-plane may be so small that the plane of movement eventually follows the bedding as offering the line of least resistance.

When the dip and strike of the fault coincide with the dip and strike of the beds, there is no apparent disturbance in the relationship of the rocks on each side of the fault-fracture.

The only evidence of the existence of such a fault is the smooth, polished, and slickensided surfaces on the plane of movement.

In some cases the movement along a *thrust-plane* has crushed the wall-rocks into fragments, forming what is called a *friction-*

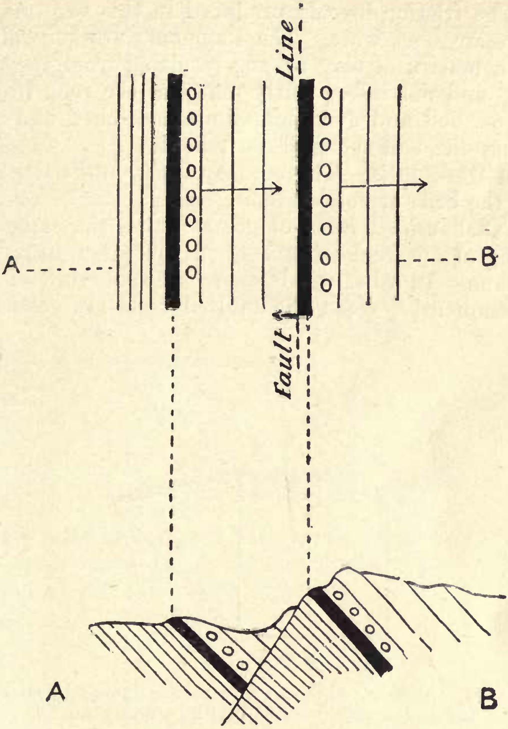

FIG. 92.—Showing repetition of inclined beds. Upper diagram is map of beds traversed by strike-fault. Lower diagram is a cross-section along line A B, showing repetition of dislocated beds.

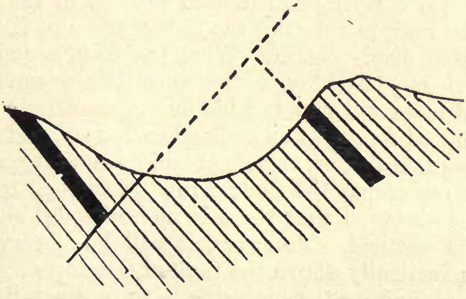

FIG. 93.—Showing coal-seam partly removed by denudation on one side along line of strike-fault.

breccia. The friction-breccia produced in this way may be a few inches or many feet wide. The fragments are generally held together in a matrix of clay or *pug* resulting from the attrition of the walls; and not infrequently many of the rock fragments are partially rounded and even sometimes scratched and striated by the grinding effect of the wall-movement.

Effect of Dip-Faults.—The course of *dip-faults* is parallel with the dip of the beds or veins intersected.

On the slickensided faces of great faults, the striæ caused by the rubbing of one rock-surface upon the other usually follow a vertical plane. In other words, there is no side shift of the faulted bed. Consequently, when the faulted beds are vertical, there is no lateral displacement or *heave*, as the dissevered ends merely slide upon one another in a vertical plane.

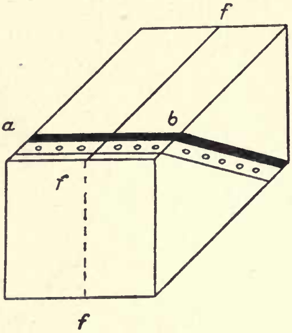

Fig. 94.—Showing dip-fault intersecting inclined coal-seam before faulting (represented by wooden model).

The apparent heave or lateral displacement is produced by the dip of the seam carrying the faulted portion of the seam to the right or left; and, manifestly, the flatter the dip, the greater will be the apparent displacement. When the seam or lode is vertical, there can obviously be no heave; for since the movement is vertical, the fractured faces will merely slide on one another.

Let *a b* in fig. 94 represent an inclined coal-seam, and *f f* a fracture. When faulting takes place, the effect will be as shown in fig. 95.

Here *m n* represents the downthrow or vertical displacement; and it will be observed that there is no horizontal shift, since the fault-plane is vertical. Moreover, it will be observed that the outcrop *m* is vertically above the faulted outcrop *n*.

When the ground on the high side is worn down by denudation to the level of *d e*, there is displayed an apparent horizontal displacement of the dissevered seam from *s* to *n*, fig. 96, and *s n* = the *heave*, which is not real but the result of the vertical movement followed by denudation. And the portion of the seam exposed at *s* by denudation does not correspond with the portion cropping out at *n*.

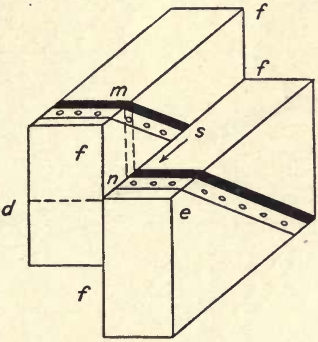

FIG. 95.—Showing displacement caused by dip-fault after faulting.

If the fault inclines to one side, as in fig. 97, then we shall have a vertical downthrow = *a b*, and a horizontal shift *b c*, which will represent the horizontal disseverment due to the faulted portion sliding on a sloping plane. And, obviously, the flatter the dip of the fault, the greater will be the *shift* for a given *throw* or vertical displacement.

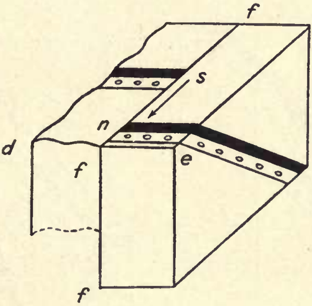

FIG. 96.—Showing apparent heave.

If now we suppose that the elevated portion of the seam is denuded down to the level of *d c*, then there will be an *apparent heave* = *s n*; but, obviously, the portion of the seam at *n* will not correspond to the portion at *s*, but to the summit of the portion of *m*, now removed by denudation.

Furthermore, when the upthrow side is denuded down to the level of *d c*, the evidence of the *horizontal shift b c* will be removed.

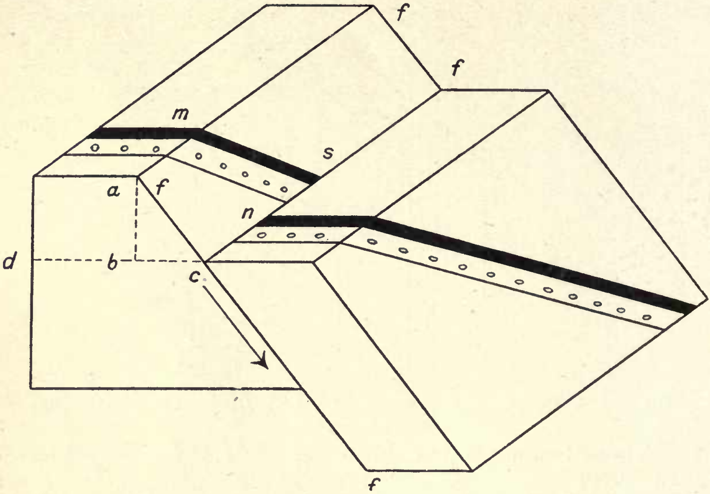

FIG. 97 —Showing effects of inclined dip-fault on tilted coal-seam.

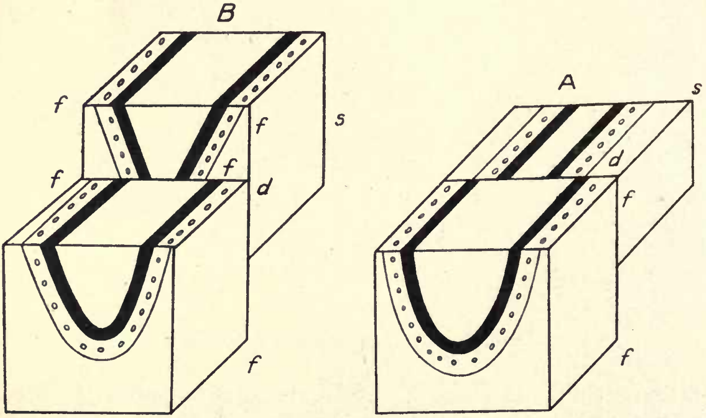

FIG. 98.—Showing effect of dip-fault on a syncline. Diagram A shows the appearance of the outcrops after faulting and denudation; diagram B, after faulting, but before denudation.

Effect of Dip-Fault on Syncline.—When a block of strata arranged in the form of a syncline is traversed by a dip-fault and the ground on the high side is denuded down to the level of the low side, the lines of outcrop on the high side will appear *inside* the lines on the low side, since they represent a narrower portion of the syncline, as shown in fig. 98.

Effect of Dip-Fault on Anticline.—The effect in this case is the opposite of that produced on a syncline; that is, the outcrops of the denuded portion will appear *outside* the lines of outcrop on the downthrow side, as shown in fig. 99.

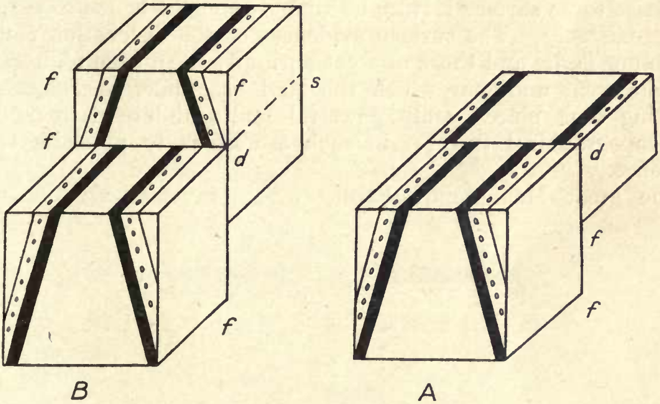

Fig. 99.—Showing effect of dip-fault on anticline.
A, After denudation. B, Before denudation.

Step-Faults.—Extensive subsidence or elevation is usually accomplished by the production of a number of parallel faults. When the dip of the different faults is in the same direction, there is frequently produced a succession of downthrows which in cross-section resemble the steps of a stair; hence the name *step-fault*.
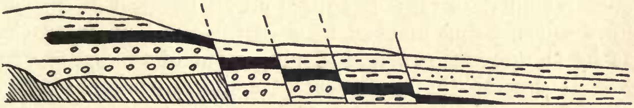
Fig. 100.—Showing effect of step-faulting.

The displacement caused by step-faults is usually small, and is best seen when the faults dislocate a coal-seam.

Trough-Faults.—When two parallel fractures dip towards one another, permitting a block of strata to be thrown down between them, they form what is spoken of as a *trough-fault*. A well-known example is the trough-fault of Dudley Port Mine in Staffordshire, which has thrown down the great 10-yard seam of coal a vertical distance of 450 feet (fig. 101).

When the area depressed by trough-faulting is of considerable linear extent, it forms what German geologists call a *Graben*.[1]

Field Evidence of Faults.—Many faults, perhaps the majority, give rise to no surface feature by which we might be led to suspect their existence. The surface evidences of the dislocation caused by minor faults and those of great antiquity have been obliterated by the wear and tear which the land has undergone since the faulting took place. Only powerful faults of late date modify the topographical features in such a way as to proclaim their presence.

The great Moanataiari Fault, which taverses the Thames Goldfield, and displaces all the gold-bearing lodes lying in its path, is of such recent date that its course may be traced on the surface for many miles, being marked by a distinct line of depression, as well as by the downthrow and displacement of the spurs which it crosses. It dips to the southwest at a uniform angle of 45°, and wherever it is cut in the mine workings its course is marked by a layer of friction-breccia and clay, varying from 20 to 100 feet thick. Its vertical displacement amounts to about 400 feet.

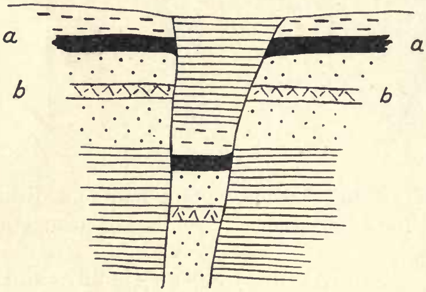

FIG. 101.—Showing effect of trough-fault.
(*a*) Seam of coal. (*b*) Sheet of basalt.

Faults are rarely visible at the surface except in bare cliffs and artificial cuttings. As a rule they are obscured with a sheet of younger detritus. Even the clean fault-fractures so frequently seen in cliffs and railway-cuttings may be mere local dislocations, or branches radiating from some greater fault.

The majority of the faults that traverse the coal-fields of Great Britain, North France, Belgium, Pennsylvania, New South Wales,

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[1] Ger. *Graben* = ditch or trench.

New Zealand, and other countries, were unknown until their presence was disclosed by the progress of underground mining.

When once the position, course, and dip of a fault are ascertained, its position in contiguous areas can be predicted with a certain degree of accuracy, provided no later faulting or dyke intrusion has diverted it from its normal course.

Since, then, the topographical effects and actual fractures of faults are seldom seen at the surface, the geologist is compelled to depend on the inference to be drawn from certain field occurrences as to the existence of faults. Thus, when two members of the same formation are found abutting against one another, as shown in fig. 102, it is inferred that a fault exists at the line of contact.

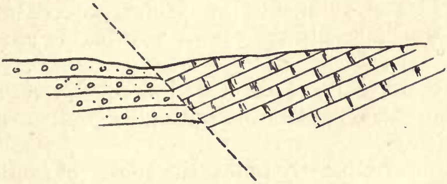

Fig. 102.—Showing existence of fault inferred from presence of abutting limestone and conglomerate.

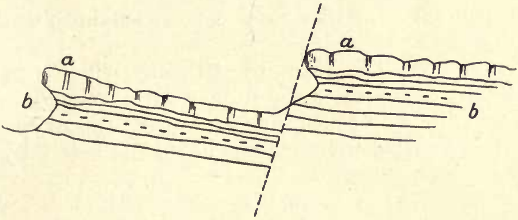

Fig. 103.—Showing existence of fault inferred from repetition of beds.

Again, the repetition of a series of beds, or of some of the beds, in the absence of folding, is always held to be an evidence of faulting, as shown in fig. 103.

Where a younger series of strata occupying the floor of a valley or inland basin is tilted on end, may be for scores of miles against an older formation, as frequently happens along the foot of a mountain-chain, the evidence is held to indicate profound dislocation or faulting of an orogenic character. Such faulting has taken place in the Great Basin of the Western States of America and in the inland basins of New Zealand in connection with the uplift of the *block* mountains in those regions.

The existence of an unseen fault may be, as a rule, determined by the detailed examination and mapping of a district. By its effect on the geological structure, the position and course of the fault, as well as its vertical displacement, can be worked out without the actual fracture being seen in a single section on the surface.

In coal areas and goldfields, the faults proved to exist by the underground workings always afford a valuable aid to the field-geologist.

Many valleys have been excavated along the course of faults; hence persistent escarpments on the valley-walls are always suggestive of faulting.

Lines of springs frequently follow the course of faults, and should be carefully noted. The sheet of stiff clay which lies along the walls of fault-fissures arrests the flow of underground water which eventually finds its way to the surface in the form of springs. The existence of a mineral vein may also be indicated by a line of springs.

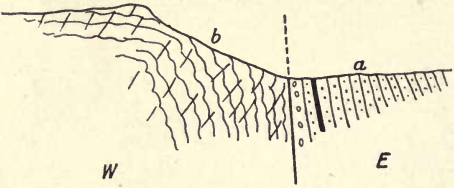

Fig. 104.—Showing faulting of young Tertiaries against mica-schist in New Zealand.

(*a*) Young Tertiary lacustrine beds. (*b*) Palæozoic mica-schist.

Cleavage.

Cleavage Structure.—Shales and other rocks composed of fine sediments possess a tendency to split into laminæ parallel to the original bedding planes, and this is the natural thing to expect from the manner in which the sediments were laid down. Many of the older fine-grained rocks, however, possess a tendency to split into plates or thin flags at *right angles* to the original stratification planes. This peculiar structure is best exemplified in roofing slates, and is called *cleavage* or, more correctly, *slaty cleavage*, to distinguish it from the natural cleavage possessed by many crystalline minerals.

Although cleavage is, as a rule, best developed when at right angles to the bedding planes, it may intersect these at any angle, or may even be parallel with them. For example, the slates at Collingwood in New Zealand possess a distinct cleavage that in different places intersects the stratification planes at various angles from 30° to 45°.

When examined under the microscope, in thin slices, the constituent particles of a slate are found to be elongated in a direction parallel with the cleavage-planes. It is this parallelism of the grains which enables a slate to split readily into thin plates.

Where the cleavage is well developed, the original stratification planes become obscure, or they may be altogether obliterated. In highly altered slates, crystalline minerals, such as mica and rutile (the former most abundantly), are frequently developed along the cleavage-planes. In this way we are able to trace the alteration of shale to slate, of slate to phyllite or mica-slate, of phyllite to mica-schist, and of mica-schist to gneiss.

Origin of Cleavage.—Cleavage is the result of enormous lateral pressure. It is generally best developed where the rocks have been subjected to intense folding combined with sufficient superincumbent weight to prevent the loss of lateral stress by the upward yielding of the strata. Near the surface the rocks will yield and fracture before the lateral pressure becomes sufficient to cause the component particles to be elongated or rearranged at right angles to the compressing force. Hence it is found that slaty cleavage is always best developed in ancient sediments that have been subjected to prolonged compression in deep crustal folds.

Sandstones, conglomerates, and altered igneous rocks frequently exhibit an incipient form of cleavage that is, however, usually short and irregular.

Slaty cleavage is not confined to rocks of any particular age, but is seldom met with in formations younger than the Jurassic. The fine roofing slates of Wales, of Cambrian age, are remarkably fissile and homogeneous in texture.

Cleavage, in all respects similar to that induced in slates, has been imitated by mechanical means in various mixtures of clay by Sorby and other experimenters.

Slates that have been subjected to a torsion or twisting stress through the obstruction offered by an unyielding buttress of granite lying in the path of the compressive force are found to break up readily into thin prismatic pencils.

SUMMARY.

Joint-Structure.—(1) The majority of sedimentary rocks, both altered and unaltered, are traversed by two sets of simple cracks called *joints*, that are usually perpendicular to the original bedding planes and at right angles to one another, thereby dividing the rock-mass into cuboidal or prismatic blocks.

Joints are commonly confined to the particular rock in which they occur, but in some cases they are found to pass from one rock to another. The best-developed joints are known to workmen as *master-joints*.

Some igneous rocks are traversed by two sets of joints that divide the rock-mass into symmetrical columns, giving rise to the well-known *columnar structure* which is particularly well developed in some basalts.

Joints are necessarily confined to the zone of fracture, and in the majority of cases they are not continuous but die out when followed in any given direction, being succeeded after an interval by others having the same general course.

Joint-planes sometimes show polished and striated faces which indicate rubbing or attrition due to some movement.

The joints that are so frequently found traversing seams of the older coals are termed *cleats*. The *face cleats* run parallel with the strike and are generally the most pronounced. The *butt cleats* are perpendicular to the face cleats. The master-joints in rocks and the cleats in coals are utilised by the workmen to facilitate the breaking of the material.

Origin of Joints.—(2) Joints are in all probability caused by tension stresses arising from folding and earth-movements resulting from shrinkage and shearing. The master-joints usually run parallel with the axis of elevation, which points to a genetic relationship between joints and folding.

In anticlinal folds, the upper layers of rock will be in tension and the lower in compression; while in a syncline, the lower layers will be in tension and the upper in compression.

Faults.—(3) A fault is a simple crack or fissure on one side of which movement has taken place so as to shift the rocks on each side relatively to one another.

Faults are caused by crustal stresses of greater magnitude than those which originated jointage. Joints and faults are closely related, and both are the visible expression of mechanical stresses. Sharp folding results in fracturing and faulting whenever the stress exceeds the elastic limit of the rock-mass.

Faults begin gradually, somewhere along their course attain a maximum displacement, and then gradually die out. Their length may vary from a few hundred feet to hundreds of miles, and their vertical displacement from a fraction of an inch to many thousand feet.

The faces of fault-planes are frequently polished, grooved, and striated—that is, *slickensided.* In many cases, perhaps the majority, the fault-fissure is filled with a sheet of clay resulting from the attrition of the rock-surfaces. In other cases they are filled with fragments of rock. In many cases fault-fissures have formed channels for the circulation of underground waters which have deposited mineral matter and metallic ores in them. Many faults have in this way become changed into valuable lodes.

(4) In what is called a *normal* fault the downthrow is towards the side to which the fault inclines; and in a *reversed* or *overlap* fault the downthrow is on the footwall side.

(5) A fault, according to the direction it pursues in relation to the strike of the rocks it traverses, may be a *strike-fault* which runs parallel with the strike, or a *dip-fault* which runs at right angles to the strike. But it must be remembered that faults may run at any angle between the strike and dip.

A strike-fault causes both vertical and horizontal displacement of the beds it intersects, and if the *throw* is considerable, may cause a repetition of the surface outcrops of a succession of beds.

(6) Dip-faults cause a vertical and an apparent lateral displacement, the last due to the dip of the faulted beds carrying the faulted portion to the right or left.

Where parallel faults cause a displacement in the same direction, they form what are called *step-faults*; and where two faults dip towards each other so as to permit a block of rock to drop down between them, they form a *trough-fault.*

(7) Among the best field-evidences of faulting are (*a*) the side displacement of beds, and (*b*) the repetition of beds where there is no reason to suspect the existence of isoclinal folding. Few faults are recognisable on the surface, as in the majority of cases denudation has kept pace with the rate of displacement. Their existence can, however, be deduced from the deposition and arrangement of the rocks, as shown by a careful geological survey. Faults are easily recognised in coal and metal mines by the displacement of the seams and lodes which they intersect.

Cleavage.—(8) This is the tendency possessed by many rocks, particularly those of fine texture, to split into thin plates in some direction not parallel to the original bedding plane. Cleavage is best seen in clay slates. It can be induced in artificial mixtures of clays, iron oxide, etc., by the application of enormous lateral pressure. The cleavage-plane is always perpendicular to the line of pressure. It is believed that slaty cleavage is the result of lateral pressure or compression arising from crustal folding.

CHAPTER XI.

COMPOSITION OF EARTH'S CRUST.

Constitution and Physical Properties of Minerals.

THE crust of the Earth is composed of rocks and minerals which, in their ultimate constitution, consist of elementary substances called elements.

Some Chemical Principles.—*Elements* are simple substances, and of these, chemical research has identified about seventy in the various rocks, minerals, and compounds that constitute the accessible portion of the crust. The majority are, however, comparatively rare.

Elements and their compounds exist naturally in three conditions, namely, the gaseous, liquid, and solid.

Most solids can be rendered liquid by the application of heat; and by applying still more heat, the liquid form can be changed to the gaseous. Conversely, by the application of sufficient cold and pressure, the gases can be made first liquid and then solid.

Of the metallic minerals, mercury is the only one that is liquid at ordinary temperatures. It can be converted into a solid by subjecting it to the influence of intense cold.

The majority of the elements do not exist in a *free* or *uncombined* state, but two, three, or more combine with one another to form various compounds. A compound may be a gas, like carbon dioxide; a liquid, like water; or a solid, like calcite or limestone.

Among the elements that exist in a free state we have the gases oxygen, nitrogen, and chlorine; the liquid, mercury; and the solids, gold, silver, platinum, copper, iron, carbon, sulphur, and some others.

Practically, all the elements resent an existence in a free state, and hence are always on the alert to form alliances with other elements or compounds.

The chemical affinities or likings of some elements for certain other elements are very powerful and for others feeble. The gas *fluorine*, for example, is so active that it can only be separated from its compounds with the greatest difficulty, and when separated it requires the exercise of extraordinary precautions to keep it from combining with other elements. On the other hand, *nitrogen*, when free, is not very active, and it is for this reason that it constitutes so large a proportion of the atmosphere.

An element may possess the power to combine with many different elements with various degrees of intensity. With those to which it is strongly attracted, it will form stable compounds, and with those to which it is feebly attached, feeble combinations that are easily broken up.

Thus *silicon* has a powerful attraction for oxygen, and when once these two elements are united, as we find them in *silica* (SiO_2), which occupies such an important place among the constituents of the Earth's crust, it is almost impossible to disassociate them. On the other hand, iron and oxygen have a mutual attraction, forming *oxides of iron*, but the oxygen can easily be displaced from the iron by presenting carbon to it under suitable conditions. In fact, the oxides of almost all the metals can be broken up by carbon, and this is the principle that underlies the reduction or smelting of the base metals.

What has been said of the elements is also true of many compounds, particularly of the gaseous compounds and the salts soluble in water. That is, they possess the power to unite with elements or other compounds to form new compounds. They also, like the elements, possess certain affinities, preferring to unite with certain elements and compounds in preference to others. Likewise with certain elements and compounds they are capable of forming stable combinations, while with others they form feeble combinations. Thus the union of lime (CaO) and carbonic acid (CO_2) is a comparatively stable compound forming calcite, limestone, or chalk; but the soluble bicarbonate of lime, which is formed when carbonic acid dissolved in water acts on limestone ($CaCO_3$), is a feeble combination, the excess of carbon dioxide being easily displaced.

The inveterate natural propensity and continual struggle of certain elements and compounds to form new and attractive combinations more to their liking, is the dominant principle underlying the weathering and disintegration of rocks which play so important a *rôle* in the general processes of denudation.

The three compounds responsible for the greater part of this disturbance are silica (chemically called *silicic acid*), *carbonic acid*, and *sulphuric acid*. Next to these we have the elements oxygen and chlorine, both active and powerful allies of the acids.

The acids unite with the oxides of the metals called bases to form new compounds. Thus :—

Silicic acid, *i.e.* silica, forms *silicates*.
Carbonic acid, *i.e.* carbon dioxide, forms *carbonates*.
Sulphuric acid forms *sulphates*.
Oxygen unites with metals to form oxides, or unites with lower oxides to form higher oxides.
Chlorine unites with metals to form chlorides.

The silicates, carbonates, and sulphates are important in any study of the crust on account of the dominant part they play as rock-forming minerals.

Of the eighty or more elements distinguished by chemical science, about twelve constitute about 97 per cent. of the mass of the accessible crust. These twelve are as follows :—

Element.	Percentage in Crust.
Oxygen,	47
Silicon,	28
Aluminium,	8
Iron,	6
Calcium,	4
Magnesium,	2
Sodium,	2
Potassium,	2
Carbon, chlorine, barium, and manganese,	about 2

Some Physical Properties of Minerals.

A Mineral Defined.—The term *mineral* embraces such a wide range of natural substances that it is difficult to formulate a definition sufficiently comprehensive and exact to satisfy scientific requirements. A mineral may, however, be defined as *a natural, homogeneous, inorganic substance possessing a definite chemical composition.*

This definition includes *water* and its solid form *ice*, but excludes coal and some other substances of vegetable origin that are by common usage regarded as minerals.

The most important physical properties of minerals are the following :—

1. Crystalline form.
2. Cleavage.
3. Fracture.
4. Hardness.
5. Tenacity.
6. Specific gravity.
7. Lustre and feel.
8. Colour and streak.

Formation of Crystals.—Crystals may be formed in Nature in three different ways, namely :—

(1) By sublimation from gases.
(2) By chemical precipitation from solutions.
(3) By separation from a fused or molten mass.

In volcanic regions the sides of the vents of *fumaroles* and of all the cavities or vughs to which the gases have access, are frequently lined with beautiful incrustations of sulphur crystals formed by sublimation through the mutual interaction of sulphuretted-hydrogen and sulphurous acid gases emanating from the ground.

The formation of crystals by precipitation from aqueous solutions is a subject of which we have many familiar examples. If a hot saturated solution of brine be allowed to cool, crystals of rock-salt will separate out from the mother liquor. Or when a string is suspended in a saturated cooling solution of sugar, it soon becomes covered with the beautiful crystals called rock-sugar or barley-sugar. The crystalline *gangue* or matrix of mineral lodes is now believed to have been formed by precipitation from mineralised waters that at one time circulated in the fissures.

A fused mass of rock is merely a solution of a thick and viscous kind, and, on cooling, crystals separate out from it just as they do from an aqueous saline solution.

CRYSTALLINE FORM.

All minerals have a tendency to occur in certain definite geometrical forms which are called *crystals*. There are hundreds of crystal forms, but all can be referred to six groups to which the name *crystallographic systems* is applied. They are as follows :—

1. Cubic or Isometric.
2. Dimetric.
3. Trimetric.
4. Monoclinic.
5. Triclinic.
6. Hexagonal.

In every crystal the flat surfaces or faces are called *planes*, and these may be flat, rough, or curved. The line formed by the meeting of two planes is an *edge*, and the point where three or more planes meet is called a *solid angle*.

All crystals may therefore be regarded as solid geometrical figures bounded by *planes* or *faces* ; and although the size of the planes may vary, as they do in large and small crystals, the angles between corresponding planes in different crystals of the same mineral are always the same. A few minerals are dimorphic.

In all crystals the planes are referred to certain imaginary lines called *axes* running through the crystal. This construction is easily understood by the examination of wooden or glass models, but can also be made clear by a few simple experiments, now to be described.

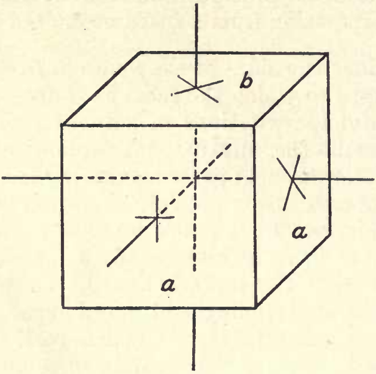

Fig. 105.—Showing cube with its three axes at right angles to one another. (*a*–*b*) Pinakoid faces.

Cubic or Isometric[1] System.—Take a piece of soap, transparent if procurable, and cut it into a cube about two inches square.

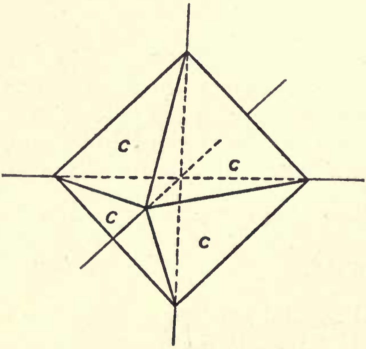

Fig. 106.—Showing octahedron. (*c*, *c*) Pyramid faces.

Through the centre of each pair of opposite planes push a fine knitting-needle, as shown in fig. 105.

It will be observed that the three needles or axes lie at right angles to one another, and that the distance from the *centre* or point of intersection inside the crystal to each plane is the same.

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[1] Gr. *isos* = equal, and *metron* = a measure.

Thus, in the cubic system we have three axes of equal length and at right angles to one another; and all the axes being equal, there is no axis that can be regarded as the principal axis in preference to the others.

If now we truncate the solid angles of the cube down to the points where the needles emerge, we shall get an eight-sided figure or *octahedron.*

By truncating various solid angles and edges we may obtain many modifications of the cube, all of which can be referred to the three axes of the cubic system.

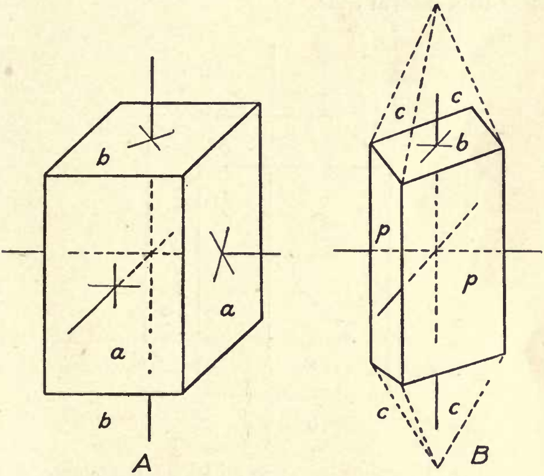

Fig. 107.—Showing prisms of dimetric system.

(*a, a*) Pinacoid faces.
(*b, b*) Basal planes.
(*p, p*) Prism faces.
(*c, c*) Pyramid faces.

Dimetric[1] **System.**—Take another piece of soap and cut it into a prism three inches long, with ends an inch and a quarter square. Mark the centre of each face, and through the marks in each pair of opposite faces push a needle.

Here we have three axes, all at right angles; two are of equal length and lie in the same plane, while the third is either longer or shorter than the others and is called the *principal* axis. In our example shown in the last figure we have made it longer than the others.

Observe that the *pinacoid*[2] faces or planes *a, a,* are *parallel* to the principal axis, and *perpendicular* to the *lateral* axes.

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[1] Gr. *dis* = double, and *metron* = a measure.

[2] Gr. *pinax* = a plank, and *eidos* = like.

The top and bottom planes of the prism are marked *b*, *b*, and are crystallographically called *basal* planes, notwithstanding their position at the top and bottom of the prism.

If now we truncate or pare away the vertical edges of the prism until the new planes meet at the points where the lateral axes emerge, as in B of fig. 107, we shall obtain a new prism, bounded at the ends by *basal* planes *b*, *b*, and at the sides with four new vertical planes lying *parallel* with the principal axis and *touching* two of the *lateral* axes. These planes are marked *p*, *p*, to distinguish them from the *pinacoids*, each of which, as we have seen above, is *perpendicular* to a lateral axis.

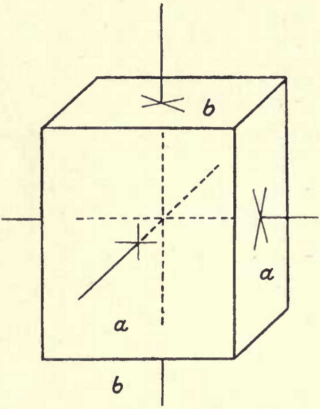

Fig. 108.—Showing prism of trimetric system.
(*a*, *a*) Pinacoids. (*b*, *b*) Basal planes.

If we take another prism similar to the first used to illustrate this system, as shown in A of fig. 107, and truncate the eight solid angles, we shall obtain an octahedron bounded with pyramid faces *c*, *c*.

Trimetric[1] System.—Cut a prism with oblong ends, and, as before, insert the needles through the centres of the opposite faces.

It will be seen that the three axes are still at right angles to one another, but that all are of different length. Here also the principal axis may be longer or shorter than either of the lateral axes.

By truncating the solid angles we obtain an octahedron bounded by pyramid faces ; and by truncating the vertical edges of another prism similar to the one we started with, as shown in fig. 108, we obtain a prism bounded by prism faces.

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[1] Gr. *treis*=three, and *metron*=a measure.

Monoclinic[1] **or Oblique System.**—In this system there are three unequal axes, two at right angles, the third inclined.

To illustrate this system, first cut a prism three inches long, with ends, say, one inch by an inch and a half. Insert a needle through the centre of the top and bottom, *i.e.* basal planes, and another through the centre of the pinacoid planes lying parallel with the longer axis. These two needles or axes will be at right angles, but are of different lengths.

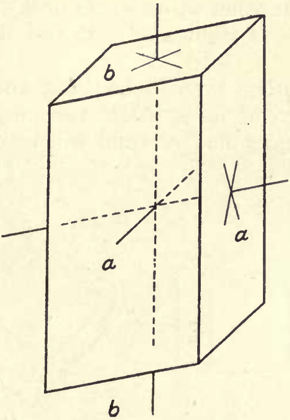

FIG. 109.—Showing prism of monoclinic system.
(*a*, *a*) Pinacoids. (*b*, *b*) Basal planes.

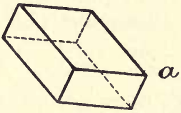

FIG. 110.—Doubly oblique prism of copper sulphate.

Now pare away the basal planes so that the model will not lie vertical when placed on the table. Make both basal planes parallel to one another, and through their centres push the third needle. The third axis will be seen to be inclined to the other two.

Triclinic[2] **or doubly Oblique System.**—In this system there are three unequal axes, and all inclined at different angles.

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[1] Gr. *monos* = single, and *klino* = I bend or incline.
[2] Gr. *treis* = three, and *klino* = I bend or incline.

Take the prism of soap used in the last experiment and pare the basal planes away in a direction at right angles to the first paring which caused the inclination of the prism. The prism will now be inclined in two directions.

Hexagonal System.—This system differs from all the others in having *four* axes, of which three are equal, lie in the same plane, and are inclined to one another at an angle of 60°. The fourth, called the principal axis, is at right angles to the others, and may be of any length.

Cut a hexagonal prism three inches long, and through the centres of the opposite pairs of faces insert the needles. By truncating the solid angles a hexagonal pyramid will be obtained.

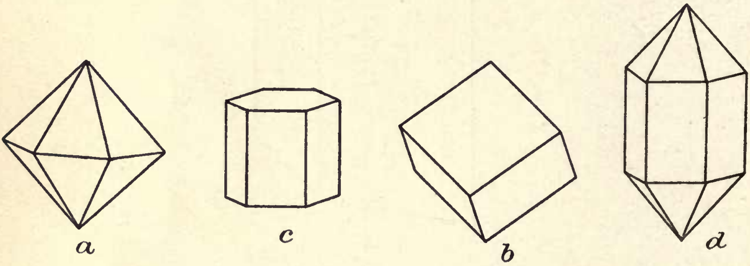

FIG. 111.—Hexagonal crystals.

(*a*) Hexagonal dodecahedron. (*b*) Rhombohedron. (*c*) Hexagonal prism. (*d*) Crystal of quartz (combination of hexagonal prism and pyramid).

RECAPITULATION OF CRYSTALLOGRAPHIC SYSTEMS.

(1) Cubic—3 axes, all equal, all at right angles.
(2) Dimetric—3 axes, two equal, all at right angles.
(3) Trimetric—3 axes, all unequal, all at right angles.
(4) Monoclinic—3 axes, all unequal, two at right angles, the other inclined.
(5) Triclinic—3 axes, all unequal, all inclined.
(6) Hexagonal—4 axes, three equal, lying in the same plane, the fourth at right angles to others.

In all the systems there may be prisms and pyramids. When crystals are very narrow and long, they are termed *acicular* or needle-shaped; and when broad, they are said to be *tabular*.

Pseudomorphs.[1]—These are crystals which have the form of one mineral and the composition of another. For example, crystals of quartz are frequently found in the form of calcite, and orthoclase is sometimes partly or entirely replaced with *cassiterite*, tin oxide.

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[1] Gr. *pseudos* = false, and *morphe* = shape.

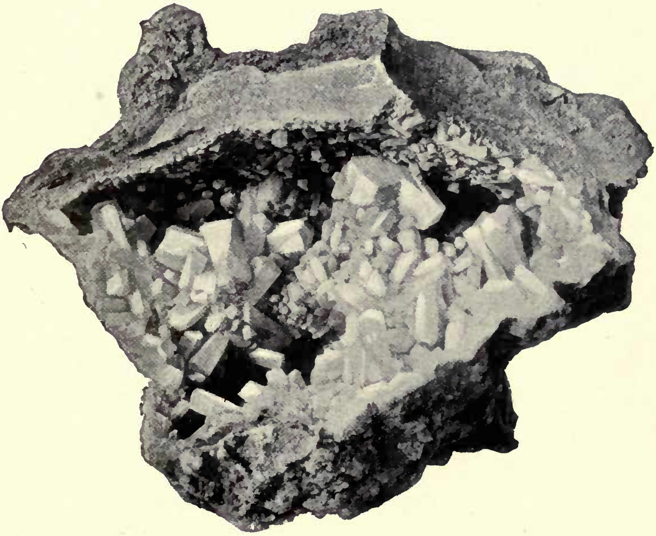

FIG. 112.—Showing geode of calcite. (After Bassler.)

Fossil organisms are frequently found replaced with *pyrites* or silica.

Pseudomorphism is the result of mineral *replacement.*

Dimorphism.[1]—A mineral substance that is capable of crystallising in two different systems is said to be *dimorphous.* Carbonate of lime is a notable example of dimorphism. In the form of *calcite* it crystallises in the hexagonal system, and as *aragonite* in the trimetric system.

Macles or Twin Crystals.—These are groups of two or more crystals that appear as if mutually intersecting one another, and sometimes as if a crystal had been cut in two and one part turned round on the other.

Macles are common in alum, albite, spinel, quartz, orthoclase, magnetite, pyrites, rutile, and many other minerals.

Geodes.—These are concretion-like masses, hollow and lined with crystals pointing inwards. They are common in all kinds of rocks and in mineral veins. The cavities which they filled are called *vughs.*

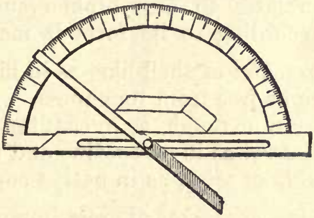

FIG. 113.—Showing simple goniometer.

Measurement of Angles of Crystals.—The angles which similar planes make with one another are constant; and since minerals always crystallise in the same forms, the measurement of the angles affords an important aid in their identification.

The angles of crystals are measured with a goniometer,[2] of which there are many mechanical and optical forms. A simple form of goniometer is shown in fig. 113.

Cleavage.—This is the tendency possessed by many crystalline minerals to split or cleave in a certain direction. The cleavages are usually parallel with the faces of one of the simple forms of the mineral. They are spoken of as *perfect* when smooth and easily obtained, and *imperfect* when rough or obtained with difficulty.

Many minerals possess no cleavage-planes; while others may

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[1] Gr. *dis* = double, and *morphe* = shape.

[2] Gr. *gone* = an angle, and *metron* = a measure.

cleave in one, two, or more directions. When a mineral possesses two or more cleavage-planes, one cleavage is generally more easily obtained than the others.

Cleavage is always in the same direction in the same mineral; hence it is of great use in the identification of crystallised minerals.

Quartz possesses no cleavage; *mica* has one perfect cleavage parallel with the basal plane; and *orthoclase* has two cleavages, viz. parallel with the basal plane, and with one pinacoid. *Calcite* has a perfect cleavage parallel to all the faces of the rhombohedron; hence, if a large crystal of that mineral be broken, it will fall into a number of small rhombohedrons, each of which may be broken into still smaller crystals of the same form.

Crystal-cleavage is a character in some way connected with the molecular structure and building up of the crystal. It has no relationship to the slaty cleavage of rock-masses, which, as we have found, is a structure induced by enormous lateral pressure.

Fracture.—This relates to any broken surface other than a cleavage-plane. According to its form it may be:—

(*a*) *Conchoidal* or shell-like, as in flint.
(*b*) *Even* or free from roughness.
(*c*) *Uneven* or rough, as in cassiterite.
(*d*) *Splintery*, as in serpentine and nephrite.
(*e*) *Hackly* or *wiry*, as in native copper.

Hardness.—This is a character of great importance in determinative mineralogy. It varies greatly in different minerals and slightly according to the face taken, and is generally expressed in terms of Moh's scale, which ranges from 1 to 10.

Moh's Scale of Hardness.

(1) *Talc*, easily scratched with finger-nail.
(2) *Gypsum*, difficult to scratch with finger-nail.
(3) *Calcite*, easily scratched with knife.
(4) *Fluor Spar*,
(5) *Apatite*,
} not easily scratched with knife.
(6) *Felspar*, difficult to scratch with knife.
(7) *Quartz*,
(8) *Topaz*,
(9) *Corundum*,
(10) *Diamond*,
} not scratched with knife.

Quartz is harder than steel; therefore it is not scratched with a knife.

A mineral is tested for hardness by finding a test-mineral which will just scratch it, and one below which will not scratch it. Its hardness lies between these.

Tenacity.—Minerals may be :—

(*a*) *Tough*, like nephrite or jade.
(*b*) *Brittle*, like tourmaline.
(*c*) *Pulverulent*, easily reduced to powder.
(*d*) *Sectile*, may be cut with a knife, like kerate.
(*e*) *Malleable*, may be flattened by hammering, like native copper.
(*f*) *Elastic*, like mica, which may be bent, but regains its original form when pressure is removed.
(*g*) *Flexible*, like asbestos, which may be bent, but is not elastic.

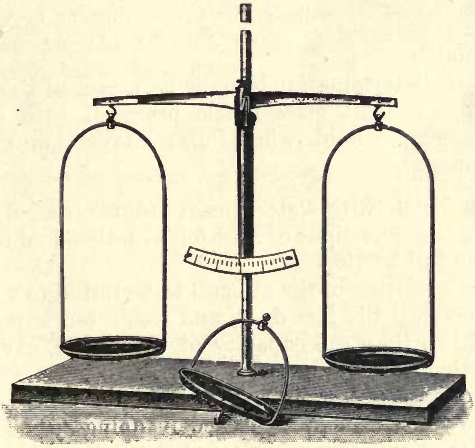

FIG. 114.—Showing specific gravity balance.

Specific Gravity = S.G.—This is the weight of a mineral compared with the weight of an equal bulk of water. The specific gravity of water is taken as 1, or unity. The specific gravity of quartz is 2·6, which means that a cubic foot of quartz, or any given volume, weighs 2·6 times heavier than the same volume of water.

A cubic foot of water weighs nearly 62·5 lbs.; therefore a cubic foot of quartz = 2·6 × 62·5 = 162·5 lbs.

Specific gravity is a character that is frequently of great use in distinguishing minerals.

To determine S.G. of a Mineral Substance heavier than Water:—First method—

(1) Weigh the substance carefully in a pair of scales. Call this the weight in air = *a*.

(2) Suspend the mineral from one of the pans by a silk thread, and weigh it in a vessel nearly full of water. Be careful to displace any air bubbles that may adhere to the surface of the mineral. Call this the weight in water $=b$.

(3) The weight in water will be less than the weight in air; that is, b will be less than a.

Subtract b from a, and the difference will be the weight of water displaced by the mineral.

(4) Divide the weight in air by the difference just found, and the quotient will be the S.G. required.

This may be expressed in the form of a simple equation:

$$\text{S.G.} = \frac{a-b}{a}.$$

Second method—

A more exact determination is made by means of a *specific gravity bottle*, which is a light glass bottle provided with a perforated stopper, arranged to hold, when full, a known quantity of water, say 500 grains.

(1) Fill the bottle with water, insert stopper, and wipe dry.

(2) Make a counterweight of lead-foil exactly equal to the weight of the full bottle.

(3) Reduce a portion of the mineral to be tested to a coarse sand. Remove all the fine dust, and weigh out a portion of the sand less than the capacity of the bottle, say 200 grains. Call this weight a.

(4) Put the weighed sand into the bottle, taking care to lose none. Some water will be displaced in doing so. The water so displaced will obviously equal the bulk of the sand introduced into the bottle.

(5) Again insert the stopper, wipe dry, and weigh, using the counterweight. It will be found that the counterweight *plus* a less weight than a will produce equilibrium. Call this weight b. Then, as before:

$$\text{S.G.} = \frac{a-b}{a}.$$

Lustre and Feel.—Many minerals possess a characteristic lustre, which may be:—

(*a*) *Metallic*, like galena;
(*b*) *Brassy*, like pyrites;
(*c*) *Resinous*, like blende;
(*d*) *Vitreous* or *glassy*, like calcite;
(*e*) *Silky*, like satin-spar and many fibrous minerals.

All the hydrous silicates of magnesia, as, for example, *talc* and *steatite*, feel *greasy* to the touch.

Actinolite and some other minerals feel *harsh*.

Colour and Streak.—The characteristic colour of many minerals is a valuable aid in their identification, especially in the case of those possessing a metallic lustre. The colour of earthy minerals is liable to great variation owing to the presence of impurities.

The *green* colour of *chlorite*,[1] *malachite*, and *glauconite*; the *blue* of *azurite*; the *scarlet-red* of *cinnabar*—are nearly always distinctive.

The *streak* refers to the colour of the powder of a mineral, and is best obtained by drawing the substance to be tested across a plate of unglazed porcelain.

The streak of metallic minerals is generally as dark, or darker, than the colour of the mineral; and of non-metallic minerals, as light, or lighter, than the colour.

Classification of Minerals.—The two systems of classification in common use are called the *Chemical* and *Economic*. In the *Chemical* classification the minerals are arranged according to their chemical composition; thus the carbonates, sulphides, oxides, and silicates are brought together into distinct groups, which are further subdivided into *hydrous*[2] and *anhydrous*.[3]

In the *Economic* classification all the ores and compounds of each metal are brought together in one group; thus, in the iron group we have metallic iron, and all the oxides, sulphides, etc., of that metal. This arrangement possesses many advantages from a commercial and technological standpoint.

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[1] Gr. *chloros* = green.

[2] Gr. *hydor* = water.

[3] Gr. *a* = without, and *hydor* = water.

CHAPTER XII.

ROCK-FORMING MINERALS.

An Account of the more Common Minerals composing the Crust of the Earth.

About three-quarters of the surface of the globe are occupied by the sea, and one-quarter by dry land. The dry land is mainly composed of such massive rocks as sandstones, shales, slates, limestone, granite, various lavas, etc., but in geology, clay, sand, gravel, and other unconsolidated rocky materials are also classed under the general term *rock*.

Rocks defined.—Many rocks are aggregates of several distinct minerals, a good example being granite, which is composed of quartz, felspar, and mica. Some rock-masses are composed of some one mineral alone in a more or less impure state ; thus marble is an impure form of calcite, and dunite an impure massive form of olivine.

Examination of Rocks.—That branch of geology which deals with the study of rock-masses as seen in the field, and with the minute structure of rocks as determined in the laboratory, is called *Petrology*.[1]

The *megascopic*[2] examination of a rock refers to the results obtained by viewing the rock with the naked eye. The *microscopic*[3] examination refers to the study of the minute structure as seen in thin slices placed under the microscope.

Minerals occur in Two Conditions.—A mineral may occur in Nature in two conditions or forms, namely :—

(1) *Crystalline*—that is, in more or less well-defined crystals.
(2) *Amorphous*—that is, massive, or without definite crystalline structure or form.

In mineralogy the crystalline form of a mineral is frequently given a distinct name ; thus the *diamond* is the name applied to

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[1] Gr. *petra* = a rock, and *logos* = description.

[2] Gr. *megas* = large, and *skopein* = to view.

[3] Gr. *micros* = small, and *skopein* = to view.

the crystalline form of *carbon*, *corundum* of *alumina*, and *selenite* of *gypsum*.

A mineral may be chemically composed of :—

One element, as the diamond, which is pure carbon.

Two elements, as ordinary table salt, composed of the metal *sodium*, and the gas *chlorine*.

Three elements, as *calcite*, the principal constituent of all crystalline limestones, composed of the metal *calcium*, *carbon* and *oxygen*.

Four or *more* elements, as the *garnet* and *mica*, which are complex and variable silicates of many bases.

Gold, silver, platinum, iron, lead, and mercury, and all the metals that occur in Nature in the *native* or metallic condition, are minerals. The chemical combinations of the metals with oxygen, sulphur, arsenic, fluorine, etc., are commonly spoken of as *ores*. For example :—

Zinc + sulphur = ZnS = zinc blende.
Lead + sulphur = PbS = galena.

All the ores of the metals are classed as minerals, and their study forms an important branch of mineralogy.

Thus we find that oxygen, sulphur, etc., possess the property of combining with metals, or *bases* as they are then called, to form a group of minerals known as *ores*. Ores commonly occur aggregated in lodes or veins and in irregular deposits. As rock-forming minerals they are not important, with the exception of the compounds of iron, which are abundant and widespread.

Silicates and Carbonates.—Oxygen, sulphur, and other elementary substances combine with the metals to form ores; but silica (SiO_2) and carbonic acid (CO_2) possess the property of being able to combine with the oxides of the metals, as bases, forming large and varied groups of minerals termed silicates and carbonates respectively. Both are important as rock-forming constituents, the former occupying the dominant place.

Take the case of carbonic acid (carbon dioxide).

Acid. Base.
Carbonic acid + lime.
CO_2 + CaO = Calcium carbonate.
Carbonic acid + magnesia.
CO_2 + MgO = magnesium carbonate.

Carbonic acid may combine with one base, as with lime, forming calcite; or with two bases, forming dolomite, the carbonate of calcium and magnesium.

Carbonate of lime and carbonate of magnesia, in both their crystalline and massive forms, compose rock-masses that are frequently of great extent.

Silica possesses all the properties of an acid, and is hence chemically termed silicic acid. Now silica, unlike carbonic acid, can combine not only with one but with two, three, or more bases in the same compound, giving rise to an exceedingly varied and numerous class of minerals of homogeneous structure and uniform composition.

Thus silica may be combined with—

One base, as in talc, the silicate of magnesia;
Two bases, as in olivine, the silicate of magnesia and iron;
Three bases, as in epidote, the silicate of alumina, lime, and iron;
Four or *more* bases, as in mica (muscovite), a silicate, of alumina, potash, and other bases.

From what has been said, we see that silica may occur in Nature as—

(1) *Free* or *uncombined*, as in quartz, which is the principal constituent of beach sand and sandstones.
(2) *Combined* with bases such as alumina, lime, magnesia, soda, potash, etc., forming the vast group of minerals termed *silicates*.

PRINCIPAL ROCK-FORMING MINERALS.

A great many minerals enter into the constitution of the crust of the Earth, but the main mass is composed of a few predominating compounds of these: *silica*, SiO_2, in its *free* and *combined* conditions constitutes more than half of the known crust.

Alumina, nearly all of which occurs combined with silica, is present to the extent of 15 per cent.

After alumina follow iron oxides, 7·5 per cent.; lime, 5·5 per cent.; magnesia, 4·5 per cent.; soda and potash, each 3 per cent. All of these, except a portion of the iron, exist in the condition of carbonates and silicates.

The principal rock-forming minerals are as follow:—

(1) Quartz.
(2) Felspar.
(3) Mica.
(4) Olivine.
(5) Serpentine.
(6) Chlorite.
(7) Hornblende.
(8) Augite.
(9) Rhombic pyroxene.
(10) Nepheline.
(11) Tourmaline.
(12) Calcite.
(13) Aragonite.
(14) Dolomite.
(15) Fluorite.
(16) Apatite.
(17) Iron ores.

Primary and Secondary Minerals.—A *primary* mineral or rock constituent is one that is developed during the cooling of the molten magma, or, in the case of a sedimentary rock, that appeared among the original constituents.

A *secondary* mineral is one that appeared after the rock-mass was formed. It is generally a product of the alteration or decomposition of one of the original or primary minerals.

Essential Mineral.—Many kinds of rock are recognised by geologists as being composed of an aggregate of certain minerals. Thus granite, as previously stated, is an aggregate of quartz, felspar, and mica. If any one of these be absent, the rock would not be recognised as a granite; hence these three are spoken of as *essential* minerals.

Accessory Minerals.—These are minerals that may or may not be present in a rock. They are *accessory* because their presence or absence does not alter the constitution of the rock, though, if abundant, they may modify it to some extent. Thus, when tourmaline is present in granite it is merely accessory.

Quartz.—This occurs in both the crystalline and amorphous or chalcedonic forms. It is harder than steel, and therefore cannot be scratched with a knife or file. On account of its great hardness it is frequently the last or ultimate residue of the detritus derived from the denudation of a land area; for while the softer materials are reduced by attrition to the condition of mud either during their transport to the sea or after they reach the sea, the quartz particles manage to survive, although doubtless greatly reduced in size.

These surviving quartz grains, sometimes angular, sometimes semiangular, and frequently rounded in shape, are piled up on sea and lake beaches, forming the familiar sea-sands found on nearly every strand.

When free from impurities, quartz is clear and transparent, but it is frequently pale-grey, pale-yellow, golden-yellow, or reddish-brown in colour owing to the presence of iron oxides. The intensity of colour becomes greater as the percentage of iron oxide increases.

Quartz is the principal constituent of sandstones, and is an *essential* constituent of mica-schist, gneiss, quartzite, rhyolite, and quartz-porphyry. As a *secondary* mineral deposited from slowly moving siliceous waters it occurs, filling cracks, fissures, and cavities. It is frequently developed in igneous rocks as a *secondary* product resulting from the alteration or decomposition of silicates.

Large bodies of quartz in the form of *siliceous sinter* are deposited by thermal springs in many volcanic regions.

Siliceous sinter is deposited in successive layers, and for that reason frequently possesses a banded or laminated structure.

When newly formed it is massive or amorphous, but in course of time it develops a finely crystalline structure.

The principal varieties of crystalline quartz are as follows :—

Rock crystal is a colourless transparent variety much used for spectacle-glasses, lenses, etc.

Amethyst, which is a purple or violet variety often of great beauty. The colour is mainly due to the presence of manganese oxide.

Cairngorm has a fine smoky-yellow or brown colour.

Ferruginous quartz possesses a yellow or reddish-brown colour due to the presence of iron peroxide. Abundant in many lands.

Among the numerous varieties of massive or chalcedonic quartz are :—

Chalcedony, found lining cavities in rocks and as stalactites. The colour is often milk-white, yellow, brown, or lavender-blue.

Carnelian, red or reddish-brown.

Flint, of various shades from grey to black. Occurs as nodules in chalk, and as beds, forming rock-masses.

Agate is a variegated and banded chalcedony.

Plasma is a leek-green variety speckled with white.

Heliotrope or *bloodstone* is a leek-green variety speckled with red.

Onyx, a banded variety of chalcedony.

Chert, a calcareous form of massive quartz, occurs in nodules and beds, and is a rock rather than a mineral.

Jasper, a massive or very finely crystalline quartz coloured red, reddish-brown, or yellow by iron oxides. In some of the older formations there occur beds of hard, fine-grained, red, or purple siliceous shales and slates, which are generally spoken of as jasperoid shales or jasperoid slates.

Among the different forms of hydrous silica are :—

Opal, which occurs in great variety ranging from *wood-opal* to the gem *noble opal*. Wood-opal is what is familiarly termed silicified or petrified wood. It is merely a replacement of wood by particles of hydrous silica.

Felspar.—This important family consists of several minerals, which show a close relationship in chemical and physical properties, as well as in their mode of occurrence.

Chemically considered, the felspars are silicates of alumina and one or more of the bases potash, soda, and lime.

The cleavage of the felspars is specially characteristic, and it enables the different species to be divided into two natural groups, namely :—

I. *Orthoclase.*[1]
II. *Plagioclase.*[2]

This subdivision is based on the direction of the cleavage-planes; for, whereas all the felspar minerals show good cleavage in two directions, in *orthoclase* felspar these two directions are at right angles to one another, and in the *plagioclase* felspars they are slightly oblique. In other words, orthoclase crystallises in the monoclinic crystal-system, and plagioclase in the triclinic.

The distinguishing character of plagioclase is the appearance of fine *lamellæ* (see fig. 139), arising from *polysynthetic* twinning, which is never exhibited by orthoclase.

Orthoclase usually presents dual twinning on various types, the commonest being the Carlsbad. Twinning may often be detected with a hand lens, but is best seen in thin sections viewed in polarised light.

Orthoclase (monoclinic) is typically a silicate of alumina and potash, consisting of silica = 64·6, alumina = 18·5, and potash = 16·9 per cent. When soda replaces the potash we get soda-orthoclase, which is a triclinic felspar. Orthoclase is an essential constituent of granite, gneiss, and syenite, in which it occurs as tabular crystals of a grey, creamy, or pink colour.

Sanidine is a clear glassy variety of orthoclase. It is a common constituent of modern acidic lavas, as rhyolite, trachyte, and obsidian.

Plagioclases or Triclinic felspars. These include two distinct species, *albite*, typically a silicate of alumina and soda; and *anorthite*, typically a silicate of alumina and lime. Between albite, which represents the acidic type of plagioclase and anorthite, the basic, there are various mixtures of these two, producing a continuous series of closely related minerals.

Let Ab = albite = $Na_2Al_2Si_6O_{16}$.
An = anorthite = $CaAl_2Si_2O_8$.

Thus the series of plagioclases includes—

Albite[3] (pure) = Ab.
Oligoclase[4] = Ab_6An_1 to Ab_3An_1.
Andesine[5] = Ab_3An_1 to Ab_1An_1.

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[1] Gr. *orthos* = straight, and *klasis* = breaking.
[2] Gr. *plagios* = slanting, and *klasis* = breaking.
[3] Lat. *alba* = white.
[4] Gr. *oligos* = small, and *klasis* = breaking.
[5] From Andes in South America.

Labradorite[1] (most acid) = Ab_1An_1.
Labradorite (medium) = $Ab_3 An_4$.
Anorthite[2] (nearly pure) = An.

For the most part the plagioclase felspars are constituents of the basic and semi-basic or intermediate types of igneous rocks, and orthoclase, with its glassy variety, sanidine, of the acidic.

Acidic and Basic defined.—An acid or acidic rock or mineral is one in which the silica or silicic acid, SiO_2, is in excess of the bases; and a basic rock or mineral is one in which the bases predominate. Take the case of orthoclase. Its composition is—

Silica, ...	64·60 per cent.
Alumina, . . .	18·45 ,,
Potash, ...	16·95 ,,
	100·00 per cent.

The silica exceeds the sum of the bases, alumina and potash; therefore this mineral is acid or acidic.

Mica.[3]—The mica family comprises a great many species, all of which occur in thin flexible plates. The micas are silicates of alumina and other bases. The most important as rock-forming minerals are as follow :—

Muscovite[4] (Potash-mica) occurs in thin transparent plates, and is an essential constituent of granite, gneiss, mica-schist, and many crystalline rocks. It is the white mica of commerce, and in plates over two inches square is of considerable value.

Biotite[5] (Magnesia-mica) is a black mica which is abundant in some granites, gneisses, and schists.

Lepidolite[6] (Lithia-mica) possesses a ruby-red or peach-blossom colour. It is found in some granites and schists.

Sericite is a colourless hydrous mica, produced by the alteration of alkali-felspar. It is also developed by the action of great pressure, and hence is abundant in schists that have been altered by dynamo-metamorphism.

Olivine.—This is a silicate of magnesia and iron. It is an essential constituent of basalt, and forms the main mass of olivine

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[1] From Labrador in North America.

[2] Gr. *a* = without or not, and *orthos* = straight.

[3] Lat. *mico* = I glisten.

[4] From Muscovy.

[5] From Biot, the French mineralogist.

[6] Gr. *lepis* = a scale, and *lithos* = a stone.

or peridotite; a rock which in some places occurs in masses of great extent.

Serpentine.—This is the hydrous silicate of magnesia and iron. It frequently forms rock-masses and also occurs in veins and nests in basic igneous rocks. It is an alteration product of olivine or other basic minerals.

Chlorite.—This is a hydrated silicate of magnesia, alumina, and iron which occurs in small dark olive-green scales, or in green earthy aggregates. It is an essential constituent of chlorite-schist, and is quite common as an alteration product of hornblende in igneous and metamorphic rocks.

Hornblende.—This is a silicate of magnesia, lime, alumina, and other bases. It includes a great many varieties, which are arranged in two groups:—

(1) Aluminous = brown or black varieties.
(2) Non-aluminous = pale-green and grey fibrous varieties.

In a general way it may be said that the dark hornblendes affect semi-basic rocks, such as diorite and andesite; and the pale green fibrous varieties acidic rocks, such as gneiss.

The dark varieties also form rock-masses, as in the case of hornblende-schist and amphibolite.

Hornblende is an essential constituent of syenite, diorite, and hornblende-andesite, but it occurs abundantly as an alteration product of augite.

The name *amphibole* is frequently used as a family name to include all the varieties of hornblende.

Augite.[1]—A variable silicate of lime, magnesia, alumina, iron, and manganese. It includes many varieties, which are generally grouped under the family name *monoclinic pyroxene.*

Like hornblende, the augites fall into two natural groups, namely:—

(1) Aluminous = dark varieties, including common augite.
(2) Non-aluminous = green varieties.

The green varieties are found abundantly in metamorphic rocks, as gneiss, crystalline limestone, and various schists; and the dark or aluminous varieties, in rocks of a basic type, as basalt, diabase, and andesite. The clear-green variety *diallage* is found in serpentine and gabbro.

Rhombic Pyroxenes.[2]—These are variable silicates that occur abundantly in many basic igneous rocks. The most common

[1] Gr. *auge* = lustre.

[2] Gr. *pur* = fire, and *xenos* = a stranger.

varieties are *enstatite, bronzite,* and *hypersthene,* the former being plentiful in serpentine and olivine rocks.

Nepheline.[1]—A silicate of alumina and soda with some potash. This is an important constituent of alkali volcanic rocks. It is always present in phonolite, and is also found in some basalts.

Some greenish and reddish massive varieties of nepheline, known as *elæolite,* occur in some syenites and ancient crystalline rocks.

Tourmaline.—A silicate of alumina, iron, and other bases. Colour generally black, but green and red varieties are not uncommon. Frequently occurs in long well-developed hexagonal prisms.

Tourmaline commonly occurs in granites, gneisses, schists, and crystalline limestones. With quartz it forms tourmaline-rock. This mineral is the nearly constant associate of tin ore.

Calcite ($CaCO_3$).—This is the principal constituent of all limestones. It is present in many shales and sandstones. As a secondary product resulting from the alteration of silicates containing lime, calcite is found filling cracks, fissures, and cavities in many igneous and crystalline rocks.

It is deposited by water in caves, forming *stalactites* which hang from the roof, and *stalagmites* which grow up from the floor.

The soft, spongy, or porous variety deposited by water at the foot of limestone cliffs and in rock-shelters is a calcareous sinter known as *travertine.*

Aragonite ($CaCO_3$).—This is the rhombic form of carbonate of lime. It composes the shells of many molluscs, but is a less stable compound than calcite. It is not abundant, being generally found in thin veins in basalt and other igneous rocks. The fibrous variety is often very beautiful.

Dolomite (Carbonate of lime and magnesia).—This forms extensive beds of massive magnesian limestone belonging to many different geological formations. It also occurs in small quantity as an alteration product of ordinary limestone and aragonite.

Fluorite (Fluoride of calcium = *fluor spar,* CaF_2).—This generally occurs in limestone formation as the gangue or matrix of lead and zinc ores.

Apatite.—This is the phosphate of lime with a little fluoride or chloride of calcium. It occurs in large crystals and as massive deposits in metamorphic rocks. Minute needles are common in many granites, schists, and basalts.

Iron Ores.—Iron in its various forms is one of the most widely distributed of all the substances that enter into the structure of the Earth's crust, being found in rocks of all kinds and all ages. It occurs combined with silica in many rocks and rock-forming

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[1] Gr. *nephele* = a cloud.

minerals, and also as separate compounds of oxygen, sulphur, etc., forming what are termed ores of iron.

Silica combines with the protoxide of iron and other bases, forming silicates. The indistinct green or bluish-green colour which is so prevalent in all classes of rock is commonly due to the presence of iron. When such rocks weather or become decomposed, the silicates are frequently broken up owing to the removal of one or more of the bases. The iron protoxide, FeO, being liberated, changes or oxidises into the peroxide, Fe_2O_3, which possesses a red or rusty-brown colour. Thus it comes about, as we so frequently find, that rocks which possess a pale-green colour in the fresh undecomposed portions, become red or rusty-brown on weathered surfaces, or even produce brick-clays that are yellow or reddish-brown.

The most abundant natural compounds of iron are as follow :—

Native iron, found in meteorites and serpentine alloyed with nickel.
Iron protoxide, FeO, not in free state, but combined with silica in many silicates.
Magnetite, Fe_3O_4, the black magnetic oxide.
Hæmatite, Fe_2O_3, the red peroxide, *i.e.* highest oxide.
Limonite or brown hydrous peroxide.
Pyrite, FeS_2, the yellow sulphide.
Marcasite, FeS_2, the white sulphide.
Pyrrhotite, Fe_7S_8, the magnetic sulphide.
Titanite (Titaniferous iron), a black, feebly magnetic mineral.
Glauconite, a dark-green hydrous silicate of magnesia and iron.

Magnetite.—This mineral is commonly found in igneous and crystalline rocks. It occurs in thick beds, irregular masses frequently of great extent, and as small grains disseminated throughout many igneous and altered rocks. In rocks subject to weathering it changes first to the carbonate and then to the brown or red peroxide. Hence sands, gravels, and compact rocks containing magnetite soon assume a rusty-brown colour on the surface when exposed to the action of air and water.

Hæmatite.—This valuable ore of iron occurs as beds interstratified with sedimentary and schistose rocks, and as a constituent of many mineral veins.

Limonite.—This ore occurs in beds and irregular deposits in stratified formations, and as the *gossan* or *cap* of sulphide lodes. In the form of *bog-iron* it is frequently found as irregular sheets on the lake-bottoms and in marsh lands where it has been deposited by the action of organic acids.

This is the oxide of iron which gives the prevailing yellow or rusty-brown colour to soils, clays, sands, and many sandstones.

Pyrite.—This mineral is present in the majority of gold, silver, copper, and other mineral veins. It also occurs as disseminated crystalline grains in slates, and many varieties of schistose rock. As a secondary product it is frequently abundant in altered andesites and other igneous rocks. It is also common as nodules and pseudomorphs in clays and shales. Pyrite in its crystalline form is a very stable compound, being hardly affected by atmospheric oxidising agents even after long exposure.

Marcasite.—This is the rhombic form of iron disulphide. It is quite common in clays, shales, coal, and all stratified formations, also in mineral veins. It decomposes very rapidly when exposed to moist air, liberating free sulphuric acid which at once attacks the minerals with which it comes in contact, forming alum, gypsum, or other sulphates.

Pyrrhotite.—This mineral is not so widely distributed as pyrite and marcasite. It occurs mostly as grains and masses, impregnating metamorphic or crystalline rocks.

Titanite.—This composes the black titanic iron-sand found on many sea-beaches. It occurs as scattered grains and plates in many igneous and metamorphic rocks. It is a very stable compound, and for that reason is able to resist weathering for a long time without alteration or oxidation.

Glauconite.—This is an important constituent of many sandstones and limestones to which it frequently imparts a characteristic green colour. It is found filling and coating foraminifera and other minute organisms, and is generally believed to have an organic origin. Glauconitic greensands are prevalent in Cretaceous and Lower Tertiary marine rocks in all parts of the globe, but are unknown now among the Palæozoic formations. It is probable that most of the valuable aggregations of iron-ore associated with the more ancient altered sedimentary rocks are composed of iron segregated from Palæozoic glauconitic sandstones and limestones.

CHAPTER XIII.

SEDIMENTARY ROCKS.

A ROCK may be composed of one or more simple minerals, or it may be a mechanical aggregate of particles derived from pre-existing rocks.

Classification of Rocks.—Rocks may be grouped in two great natural classes, namely :—

I. *Sedimentary* or *Aqueous.*
II. *Igneous.*

The altered forms of sedimentary and igneous rocks constitute a third class :—

III. *Metamorphic.*

The grouping of rocks as *Sedimentary* and *Igneous* is purely genetic and therefore based on a scientific principle. The class *Metamorphic* does not possess the same value, as it merely comprises altered forms of rocks that, in their unaltered condition, are included in the other two classes. Its use, however, may be defended on the grounds of expediency and convenience.

Sedimentary Rocks.

Sedimentary rocks, as the name implies, are composed of sediments that were laid down by the agency of water; hence the equivalent name *Aqueous* so frequently applied to them. They are also called *Clastic* or *Fragmentary*, but the second of these is open to the objection that many masses of igneous rocks are fragmentary, but in no sense sedimentary or aqueous.

Sedimentary rocks that are composed of material derived from the denudation of pre-existing rocks are said to be *detrital* ; that is, *mechanically formed.* Those formed by the accumulation of organisms, either calcareous, siliceous, or carbonaceous, are termed *organic* ; while the minerals that accumulate on the floor of lakes and inland seas as the result of chemical precipitation or evaporation are called *chemical.*

Here we have a basis for a threefold subdivision of sedimentary rocks :—

1. **Detrital.**
2. **Organic.**
3. **Chemical.**

These three groups are further subdivided as under :—

1. Detrital
   - (*a*) Arenaceous [1]—Sandy and pebbly rocks.
   - (*b*) Argillaceous [2]—Clays and shales.
2. Organic
   - (*a*) Calcareous [3]—Limestones.
   - (*b*) Siliceous [4]—Cherts and flints.
   - (*c*) Carbonaceous—Coals.
   - (*d*) Ferruginous [5]— Ironstones.
3. Chemical
   - (*a*) Carbonates—Limestones.
   - (*b*) Sulphates—Gypsum.
   - (*c*) Chlorides—Rock-salt.
   - (*d*) Silica—Siliceous sinter.

Detrital Group.

ARENACEOUS ROCKS.

The main types of rock included in this group are :—

1. Breccia.
2. Conglomerate.
3. Sandstones and gritstones.

Breccia.[6]—This is a rock composed of angular fragments of stone cemented in a paste of sand or mud, or set in a matrix of carbonate of lime, silica, or oxide of iron (Plate XV.).

Breccias were formed in places where frost-formed screes or talus-slides descended into sheltered bays or lake-basins in which the material was spread out near the shore without being subjected to the wear and tear or sorting action of rapidly-moving currents.

Breccias, from the nature of their formation, may sometimes attain a great thickness, but they seldom cover an area of large extent.

Some breccias exhibit a rude stratification, and in places where they have accumulated slowly they may even contain fossils. As a rule, however, they are not fossiliferous.

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[1] Lat. *arena* = sand.

[2] Lat. *argilla* = clay.

[3] Lat. *calx* = lime.

[4] Lat. *silex* = flint.

[5] Lat. *ferrum* = iron.

[6] It. *breccia* = a crumb (pronounced bréchia).

To face page 200.] [PLATE XV.

QUARTZITE AND CHERT BRECCIA—UTAH. (U.S. Geol. Survey.)

Many breccias contain a variable proportion of water-worn material, and some are known to pass in the same plane into coarse conglomerate.

A breccia composed principally of angular slaty fragments is called a *slaty-breccia*; of sandstone, a *sandstone-breccia*; of mica-schist, a *mica-schist-breccia*; of quartz, a *quartzose-breccia*, and so on.

The fragments composing a breccia may range from less than an inch to many feet in diameter.

Not infrequently a bed of very coarse breccia riding hard on an old shore-line is found at the base of a conglomerate. Such a breccia may contain angular masses of rock ten feet or more in diameter, torn from the bed-rock on which it rests. Such a deposit would appear to have been formed by the undercutting of steep sea-cliffs, at the foot of which the water was too deep for the fallen blocks to be subjected to the pounding and rounding effects of wave-action.

FIG. 115.—Showing breccia. (After Davis, *U.S. Geol. Survey.*)

Moraine-breccias have been formed where the angular ice-borne material was shot into a lake, estuary, or fiord; or left when the ice melted.

Fault- or *Friction-breccias* are frequently found on the walls of great faults where they were formed by the crushing and breaking up of the wall-rock during fault-movements.

Friction-breccias also occur on the walls of many large lodes. They are an evidence that movement has taken place since the filling and consolidation of the lode-matter. Breccias of this kind are generally lens-shaped. Only in rare cases are they co-extensive with the lode itself. Not infrequently the lode-matter itself is found to be brecciated, showing (*a*) that the movement took place before the lode-filling had become hardened, or (*b*) that the wall-rock was stronger than the filling.

Shear-breccias occur along the course of shear-zones. They have arisen from the crushing and shattering of the county-rock traversed by a shear-plane, and the subsequent cementing of the fragments by the infiltration of silica, oxide of iron, or carbonate of lime.

Wedges of hard rock that have become entangled in great overturned folds are frequently found to be crushed and brecciated.

Friction and shear-breccias are sometimes called *crush-breccias.* They are purely dynamical in origin, and hence fundamentally different from ordinary sedimentary breccias from which they are not always easily distinguished.

Sedimentary breccias afford valuable evidence of former terrestrial conditions. They tell us, for example, of the existence of high land near the ancient strands, of frost and glacier action. Crush-breccias, on the other hand, help us to distinguish the zones of rock that have been subjected to intense folding, shearing, and faulting.

A certain class of fragmentary volcanic rock is called a *volcanic-breccia,* a description of which will be found in the chapter dealing with igneous rocks.

Conglomerate.—This is a rock composed of consolidated gravel or shingle. The material comprising a conglomerate is water-worn and well-rounded, and has given rise to the popular name *pudding-stone.*

The constituent pebbles usually represent the hardest rocks in the region, or those hard enough to survive the wear and tear of fluviatile or marine transport. But conglomerates formed at the foot of sea-cliffs in sheltered bays may be composed of limestone pebbles, or of other rocks not noted for their hardness. Such conglomerates are not common.

A conglomerate that contains a considerable proportion of angular rock-fragments may be called a *breccia-conglomerate.*

When the pebbles in a conglomerate are mainly granite, the rock is called a *granite-conglomerate*; when sandstone, a *sandstone-conglomerate*; when quartz, a *quartzose conglomerate*; and when schist, a *schist-conglomerate.*

The cementing medium may be a matrix of fine sand or mud, carbonate of lime, silica, or oxide of iron. The descriptive name of the conglomerate may be qualified by an adjective denoting the nature of the cementing matrix. Thus, if the cement of a quartzose-conglomerate is oxide of iron, the rock might very well be called a *ferruginous quartzose-conglomerate*; or if silica, as we find in the gold-bearing *banket* of the Transvaal, we may call the rock a *siliceous quartzose-conglomerate.* These names for all purposes, except perhaps the exact petrological description, would be shortened to *ferruginous-conglomerate* and *siliceous-conglomerate.*

Conglomerates are essentially shore-deposits, and where they were formed slowly may contain fossils mixed with the constituent pebbles and sands. Some of the boulders and pebbles may be fossiliferous, but obviously such fossils were *derived* from an older rock-formation, and therefore do not indicate the age of the conglomerate. It is quite possible, for example, for a Tertiary conglomerate to contain fossiliferous boulders derived from a Silurian formation. Moreover, a conglomerate may contain rocks that have appeared as constituents of different formations. Thus, in the King County of New Zealand there is a coarse conglomerate at the base of the Lower Tertiaries mainly composed of granite, gneiss, and crystalline schists derived from a still coarser conglomerate interbedded with the neighbouring Triassic rocks.

Conglomerates, as might be gathered from the manner in which the original gravels were formed, thin out rapidly when traced seaward from the old strand. They are frequently intercalated with tapering beds of sandstone and shale.

What are called *crush-conglomerates* are sometimes found on the walls of powerful faults. They consist of large fragments of wall-rock that have become more or less rounded, polished, and sometimes striated with the rolling and kneading action to which they have been subjected during the fault-movements. The boulders are usually embedded in a matrix of stiff clay composed of crushed rock. The origin of a crush-conglomerate is purely dynamical.

Sandstones and Grits.—Sandstones are merely consolidated sands.

River and sea-sands are principally composed of quartz grains, but the composition of the sand in any given locality depends principally on the nature of the country from which it is derived.

Sands derived from the denudation of granite, gneiss, mica-schist, or sandstone consist mainly of quartz frequently associated with a small amount of magnetite, rutile, zircon, garnet, and tourmaline. If the sands occur in a situation where they have not been subjected to much attrition by wave-action or sea-currents, they may contain a small percentage of mica and orthoclase. The so-called *black sands* of New Zealand are principally composed of magnetite and quartz grains, the prevalence of the magnetite in places being due to its concentration by the laving action of the advancing and retreating tides.

Sands derived from volcanic rocks frequently contain a considerable proportion of titanic iron and magnetite, and in some cases olivine, augite, and hornblende.

In a general way it may be said that the sands resulting from denudation are the residues of the hardest rock-components in the region. Quartz is at once the hardest and most abundant of all the rock-forming minerals, and for these reasons it is the principal constituent of nearly all sands.

Sand grains are not always quartz or other simple mineral. In many coarse sands they are found to consist of small rock-particles. This is particularly the case in desert sands which often consist mainly of comminuted rock. And whereas in water-formed sands, quartz is the principal constituent in the majority of sands, comprising over 95 per cent. of the total volume, in desert sands, while still the dominant constituent, it is frequently accompanied by considerable amounts of felspar, olivine, augite, hæmatite, and other minerals that would be too soft to survive the wear and tear to which sea-borne sands are exposed.

The cementing medium or matrix of sandstones may be carbonate of lime, silica, oxide of iron, or clay.

Carbonate of lime forms *calcareous sandstones.*

Silica forms *siliceous sandstones.*

Oxide of iron (limonite) forms *ferruginous sandstones.*

Clay as a matrix forms *argillaceous sandstones.*

When the iron-oxide matrix occurs in large quantity, the rock is sometimes called a *limonitic sandstone*; and in places where the iron oxide is present in large excess, the rock may pass into an *ironstone.*

In the majority of sandstones the grains are rounded, but in some arenaceous rocks they are subangular or angular.

The colour of sandstones is generally due to the presence of some oxide of iron which may impart straw-yellow, yellowish-brown, dark-brown, red and green hues according to the degree of oxidation and hydration.

Glauconitic sandstones, generally called *green sands,* are composed of quartz grains coated with the mineral glauconite,[1] or of glauconite grains that are frequently the internal casts of foraminifera.

Glauconite, which is a hydrous silicate of iron with potash and other bases, is found filling or coating foraminifera and other marine organisms on the sea-floor off the coast of South Carolina. It possesses an olive or blackish-green colour, and hence imparts a characteristic green colour to marls, limestones, and sandstones, in which it occurs.

A sandstone containing much mica may be described as a *micaceous sandstone,* and one charged with carbonaceous matter, a *carbonaceous sandstone.*

Sandstones that split easily into thin slabs are called *flagstones*; while those that possess no distinct bedding are frequently spoken of as *freestones.*

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[1] Gr. *glaukos* = sea-green.

Many of the more ancient sandstones contain a considerable amount of felspar, and are called *felspathic sandstones* or *greywacke*, to which reference is made further on.

Calcareous, argillaceous, and ferruginous sandstones are usually soft and easily cut into blocks; the greywackes are hard and frequently much jointed and broken; while siliceous sandstones, which consist of quartzose sand set in a siliceous matrix, are intensely hard and brittle.

The sands of which sandstones are composed were laid down in a river-bed, or on the floor of some estuary, sea, or lake. Hence the character of the contained fossils will be a record of the local conditions of deposition. Thus marine shells will indicate deposition in the open sea; estuarine shells and the remains of land plants, estuarine conditions; freshwater shells and freshwater fishes with plant remains, lacustrine conditions.

Some sandstones exhibit fine examples of false-bedding, while those of a felspathic character sometimes show a tendency to weather in spheroidal forms, the partings of the different layers being marked by iron-stained seams.

Among well-known examples of sandstones we have the Colley Sandstone (Surrey), of which Windsor Castle is built; the Stanley Sandstone of Shropshire, used for grindstones and bridge-building; the Brunton Sandstone of Yorkshire; the Craigleith Sandstone of Edinburgh; and the Old Red Sandstone of Scotland. Some well-known sandstones in the oversea dominions are :—

The *Desert* Sandstone—Queensland.
The *Grampian* Sandstone—Victoria.
The *Hawkesbury* Sandstone—New South Wales.
The *Cave* Sandstone—Cape and Orange States.
The *Forest* Sandstone—Rhodesia.
The *Beacon Sandstone*—South Victoria Land, Antarctica.

Grits, or *gritstones* as they are sometimes called, are composed of coarse angular grains usually cemented in a matrix of silica or limonite.

Gritstones composed of material derived from disintegrated granite are frequently difficult to distinguish from the parent rock, particularly when they rest directly on it.

A gritstone composed of quartz grains is called a *quartzose gritstone*; and one that contains besides quartz a considerable proportion of felspar, slate, and felspathic material, constitutes a *greywacke*.

Many Palæozoic and Lower Mesozoic sandstones are greywackes. They appear to be formed of detritus derived from the denudation of land surfaces in which igneous rocks largely prevailed. When fine-grained they are sometimes difficult to distinguish from igneous rocks as seen in the field.

Greywackes frequently alternate with shales and conglomerates. They are found of all degrees of texture from fine-grained to coarse gritty rocks that sometimes approach a breccia in texture. The prevailing colour is a dark greenish-grey, but pale-green and purple varieties are common among the Palæozoic formations. Some of the grey and green varieties are in places brecciated with peculiar thin angular flakes or splinters of dark slate.

The Silurian and Devonian greywackes of some regions contain a rich and varied fauna.

ARGILLACEOUS ROCKS.

The fine sediments resulting from the decomposition of silicate minerals are mainly composed of hydrous silicate of alumina, which in its pure state is known as *Kaolin* or *China-clay*. The majority of clays are not pure, but contain more or less admixture of rock-flour, resulting from the mechanical erosion of rocks by glaciers, running water, or wave-action.

The fine sediments laid down on the sea-floor and in estuaries and deltas is generally called *mud*. Hardened mud may form massive beds of mudstone that possess no lamination, but more commonly it is finely banded with thin layers or laminæ that easily split apart, forming what is geologically called *shale*.

The muds, of which shales and mudstones are composed, were, as a rule, laid down in deeper water than the sands of sandstones. When traced landward, muds graduate into sands, and in the seaward direction pass into limestone.

Clay rocks when hardened by compression and cleaved by pressure are converted into *slates*.

A slate in which *mica* has been developed by pressure and molecular change is called a *micaceous slate* or *phyllite*.

Thus, according to the degree of hardening and alteration, we get a series of argillaceous rocks, beginning with muds and clays, that pass progressively into shale, slate, and phyllite.

Slates, shales, and marly clays that have been invaded by igneous dykes are sometimes changed into an intensely hard, brittle, fine-grained black rock called *Lydian Stone* or *Hornstone*.

Muds containing from 5 to 20 per cent. of carbonate of lime form *marls* or *marlstones*. A sandy shale is called an *arenaceous shale*, while one in which there is present sufficient carbonaceous matter to be easily distinguishable is spoken of as a *carbonaceous shale*. A shale containing bituminous matter forms an *oil-shale*. When a shale contains easily recognisable scales of mica, we get a *micaceous* shale.

Clays, marls, shales, and slates frequently contain fossils which, in the last two, may be flattened and distorted by pressure. In many shales the fossil are replaced by pyrite. The shales associated with coals are usually of estuarine or deltaic origin, and hence frequently contain an abundance of plant remains, impressions of leaves being in many cases beautifully preserved along the lamination planes.

Loam is a mixture of sand and clay with usually some carbonate of lime. Most loams are of alluvial origin, and for that reason are mostly found on the floor of river-valleys.

Boulder Clay, or *Till* as it is called in Scotland, is a more or less gritty, subglacial clay frequently crowded with angular and subangular blocks of stone. It varies greatly in composition, even within the limits of a small area. In one place it may be clayey, in another sandy ; or again it may pass with startling suddenness into gravelly beds.

Fuller's Earth is a greenish-brown, greenish-grey, bluish or yellowish soft earthy mineral with a greasy feel. Like kaolin, it adheres to the tongue, and when placed in water it falls into powder, but does not form a paste. It possesses great absorbent properties which enable it to remove grease and oily matters from cloth; hence its name Fuller's Earth.

China-clay or kaolin and *pipe-clays* are generally found in the neighbourhood of granitic masses, the hydrous silicate of alumina of which they are composed having been liberated by the decomposition of the felspar (orthoclase). They are concentrated by the rain and streams into layers and beds. Occasionally they are found as veins filling rock-fissures.

The underclays of many coal-seams are often found to be almost free from lime, alkalies, and iron and other fusible bases. Hence they possess great fire-resisting properties, being what is termed *refractory*. Such clays are called *fire-clays*. They are ancient soils from which the lime and alkalies have been exhausted by the coal-vegetation.

Gannister is a close-grained, highly siliceous variety of fire-clay found in the Lower Coal Measures of North England. It is of great value for the manufacture of gas retorts and furnace linings.

Brick-clays are impure clays, in many cases resulting from the decomposition of rocks *in situ*.

Loess is a fine wind-borne dust, in some places of glacial, in others of desert origin. It is mainly derived from the mechanical pulverisation of rocks by moving ice or desert winds. It covers large areas in Northern China, and in the valleys of the Rhine and Mississippi

Laterite is a reddish-coloured ferruginous clay found in many tropical and subtropical lands. It is formed by the subaerial decomposition of rocks *in situ*, especially in flat, low-lying jungle lands where the drainage is feeble. The decomposition of the rock is accomplished by the removal of the silica and the concentration and oxidation of the iron. Considerable deposits of laterite occur in the basalt covered areas of the Deccan. When dried, it frequently forms hard surface layers sometimes called *clay-pans*.

ORGANICALLY FORMED ROCKS.

(*a*) Calcareous.
(*b*) Siliceous.
(*c*) Carbonaceous.
(*d*) Ferruginous.

CALCAREOUS ROCKS.

The rocks of the Calcareous group are essentially composed of carbonate of lime. The principal varieties of limestone are as follow :—

1. Chalk.
2. Coralline limestone } forming massive limestones.
3. Shelly limestone } forming massive limestones.
4. Crystalline limestone or marble.
5. Argillaceous limestone.
6. Siliceous limestone.
7. Magnesian limestone or dolomite.

Chalk.—This is a very pure form of earthy limestone mainly composed of *Foraminifera* and other allied calcareous organisms that lived in clear water beyond the reach of sandy or muddy sediments.

Coralline Limestone.—Some coralline limestones, like the beautiful Oamaru stone of New Zealand, are so soft that they can be easily sawn into blocks of any desired size. Others have been hardened by the infiltration of calcareous waters. The softer varieties are generally found to be composed of broken corals, bryozoans, foraminifera, echinoderm spines and plates. In some of the harder varieties the organic structure has become obliterated, thus giving rise to what may be called a *massive limestone*. In many massive limestones the only fossils that can be distinguished are those that appear on the weathered surfaces.

The so-called *Petit Granit* of Belgium is a dense black crinoidal limestone containing fragments of shells, corals, and crinoids. It is a valuable building-stone.

Shelly Limestone.—This is a limestone mainly composed of shells of molluscs that lived in comparatively shallow water where they were liable to be mixed with sandy matter and pebbles; hence such limestones are frequently impure. Shelly limestones in many places occur in irregular beds or lens-shaped tabular masses, and they frequently alternate with sandy beds or conglomerates.

A limestone containing sandy matter is called an *arenaceous limestone*, and one mixed with pebbles a *pebbly limestone.*

Some Tertiary limestones are composed of freshwater and land snails.

Crystalline Limestone or Marble.—In this rock the original organic structure has been completely obliterated by the development of a granular, crystalline structure. Crystalline limestones are found in stratified formations of nearly all ages, but are particularly prevalent in the older Palæozoic systems. They vary in colour from the finest white statuary marble of Carrara in Italy to the dark mottled and veined varieties found in Ireland. Some of the ancient limestones contain grains and nests of graphite occurring throughout the whole mass or confined to certain horizons of the rock.

Magnesian Limestone or Dolomite.—Almost all limestones contain a small percentage of magnesium carbonate. By a process of partial replacement of the calcium carbonate and concentration of magnesium carbonate, the rock is converted into a dolomite.

In the bore-holes put down at Funafuti in the Ellice group lying north of Fiji, dolomitisation of the coralline and foraminiferal rock was found to have taken place from 600 feet downward to 1114·5 feet, the greatest depth reached, resulting in the formation of magnesian limestone with as much as 40 per cent. of magnesium carbonate. This magnesian limestone closely resembled the dolomitic limestone of the Tyrol, which occurs at a height of 10,000 feet above sea-level.

The dolomites found associated with rock-salt and gypsum have not been formed in the same way as the massive dolomites referred to above. They have been deposited as chemical precipitates on the floor of saline lakes that had reached a stage of decadence through insufficient supplies of inflowing water.

Argillaceous Limestone.—Earthy or chalky limestones containing a considerable proportion of clayey matter constitute what is termed an *Argillaceous* or *Hydraulic Limestone.* The constituents of this rock are such that when it is calcined and pulverised, the resulting powder forms a natural cement which possesses the property of setting under water; hence the name *hydraulic cement.*

Siliceous or Cherty Limestone.—Bands of siliceous limestone are frequently met with among the older stratified formations. In some limestones of this class, the carbonate of lime has been replaced by iron oxides, that are in many places of great commercial value.

Carbonaceous Limestone.—A limestone containing a considerable proportion of carbonaceous matter of vegetable or animal origin is called a *Carbonaceous* or *Bituminous Limestone.* Such rocks often give off a fetid smell when struck with a hammer, or when two pieces are rubbed together, and are therefore spoken of as *Stinkstone.*

Oolitic Structure.—Many of the Mesozoic limestones possess an oolitic structure; that is, they are made up of minute rounded grains about the size of a small pin-head, cemented together so closely that the rock presents the appearance of fish-roe; hence the name *oolite*[1] or *roe-stone.*

The origin of this peculiar structure is still uncertain. The grains consist of calcite possessing a radial and concentric structure. In many cases a grain of sand or a fragment of shell appears to have formed the nucleus around which the calcite formed. The carbonate of lime may have been deposited from solution on the floating earthy nuclei, just as moisture in a saturated atmosphere will collect on particles of dust.

The oolitic limestones furnish valuable building stones in almost every quarter of the globe. The *Ham Hill Stone* of Somerset; the *Portland Stone* of Dorsetshire, used in the erection of St Paul's Cathedral, London; the *Caen Stone* of Normandy; the *Swabian Stone* of Würtemburg; the *Boticino Stone* of North Italy; the *White Stone* of Kentucky—are some well-known examples.

The oolitic ironstones of Cleveland and Northampton, in which the grains consist of carbonate and oxide of iron, have been shown to result from the alteration of ordinary oolitic limestone.

Cone-in-Cone Structure.—Concretions of limestone in Cretaceous formations are frequently covered with an outer layer of limestone generally from two to four inches thick, composed of a mass of radial, fibrous, funnel-shaped, crystalline forms that fit into each other, producing a *cone-in-cone* structure. The origin of this structure is not yet well understood.

SILICEOUS ROCKS.

Cherts and Flint.—Many of the older limestones are intercalated with sheets or lens-shaped masses of siliceous rock called *Chert,* which is mainly composed of the tiny siliceous shells of *Radiolaria,* the siliceous cases of *Diatoms* (diminutive plants of a low type), and the spicules of sponges. The silica is carried in solution

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[1] Gr. *oon*=egg, and *lithos*=stone.

in sea-water, and these organisms are able to extract it for the building of their coverings or skeletons.

Chert is generally a fine-grained buff-grey, dark-grey, or black rock. It is brittle, and breaks with a conchoidal fracture. The siliceous organisms of which it is composed are set in a cement of secondary silica deposited by infiltration.

Beds, lenticular tabular masses, and nodules of *Flint* frequently occur in chalk and other earthy limestones. The nodules are generally arranged in layers parallel with the bedding planes. Like chert, flint is composed of silica extracted from sea-water by radiolarians and diatoms.

The soft incoherent forms of diatomaceous earth are called *Infusorial Earth* or *Tripoli.* They are commercially valuable as the base or matrix of many nitro-glycerine compounds, the tiny siliceous shells possessing great absorbent properties.

CARBONACEOUS ROCKS.

These rocks include the different varieties of coal and graphite.

Coal is altered vegetable matter. It consists essentially of carbon combined with oxygen, hydrogen, nitrogen, and a certain amount of earthy matter which is left as a residue, or ash, when the coal is burnt.

The progressive changes that take place in the formation of coal are seen in the different varieties of that mineral, ranging from peat to anthracite.

Peat.—Consisting of decomposing vegetable matter.
Lignite.—Compressed and altered peat showing woody structure.
Brown Coal.—Altered lignite showing no woody structure.
True Coal or **Bituminous Coal.**—Cokes or cakes when burnt.
Anthracite.—Consists mainly of carbon.

Peat consists of stems, roots, leaves, and mossy vegetation, and may be seen in process of formation at the present day on the sites of ancient forests, and on moss and heath-covered water-logged lands. In recently formed peats, the vegetable matter is only slightly altered; while in the older peats, it is partially carbonised owing to the escape of some of the oxygen and hydrogen.

Lignite [1] is a peaty accumulation that has become covered with sediments. It represents the second stage in the formation of coal; and although the woody structure of the vegetation is still well preserved, there has been a considerable elimination of water and gaseous products.

Brown Coal is the next phase. It represents a greater degree

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[1] Lat. *lignum* = wood.

of alteration than lignite. Some of poorer qualities cannot be distinguished from lignite, while many of the better grades approach a true coal.

True Coal, or **Bituminous Coal** as it is frequently called, represents a still higher degree of alteration, and in it all trace of the original woody structure has generally been obliterated. Microscopic examination, however, shows that many coals are composed of the spores of plants allied to ferns, club-mosses, and horse-tails. Others consist mainly of woody fibre and bark.

Anthracite[1] is the hardest coal. It consists almost entirely of carbon, practically all the gaseous products having been eliminated.

The anthracites of Wales and Pennsylvania are Carboniferous; and the semi-anthracites of New Zealand, Eocene. At Malvern, in the last-named state, the brown coal has been converted into anthracite by contact with a sheet of basalt.

Composition of Coal.—The constitution of coal can be very well shown by a simple test:—

(1) Weigh out 100 grains of finely powdered coal; place in a platinum dish and dry carefully at a temperature not exceeding 212° Fahr. The loss of weight = the water.

(2) Place the dish over a Bunsen burner with the lid of the dish tipped slightly to one side. Apply a dull red heat and burn off the volatile gases. The loss = volatile *hydro-carbons*, and the residue = *fixed-carbon* plus *ash* = *coke.*

(3) Remove lid; tip the dish slightly to one side and burn off the carbon, keeping the heat going until only a grey or reddish-grey ash remains. The residue = *ash*; and the ash subtracted from the weight obtained in (2) gives the *fixed-carbon.*

If a fine balance is available, 10 grains of coal will be sufficient for the test. Tabulating the results, we may get, for example:—

Water,	2·00
Hydro-carbons,	34·00
Fixed-carbon,	62·50
Ash,	1·50
	100·00

Cannel is a dull earthy shaly variety of coal often possessing a conchoidal fracture. It contains a large amount of coal gas, and for that reason is valuable for gas-making. It sometimes contains

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[1] Gr. *anthrax* = carbon.

shells and fossil fish, and may pass at its edges into bituminous shale. These facts would indicate that cannel is not formed of vegetation that grew in place, but is *detrital*; that is, composed of drift-vegetation that settled on the floor of shallow lagoons.

Jet resembles cannel coal, but is harder and blacker, and takes a fine polish. It is found at Whitby in Yorkshire, and elsewhere. Its lightness renders it suitable for personal ornaments.

Conditions of Coal Formation.—Coal is the result of the growth of a dense jungle-like vegetation on low-lying swampy areas on the sea-board near the mouth of great rivers. The deltas of the Mississippi and the swampy forests of the Amazon and Orinoco probably approach the conditions in which the coal vegetation flourished.

The coal is generally found resting on an *under-clay,* which is the soil in which the vegetation grew. In the coals of Westphalia and Nova Scotia, there have been found the remains of trees still standing in the position in which they grew, with their rootlets penetrating the under-clay. This evidence supports the contention that many coals now occupy the original sites on which the forests grew.

After centuries of growth, the accumulation of decaying vegetable matter became buried under a covering of sands when the coastal lands subsided and became submerged.

The existence of numerous seams of coal in the same formation separated by beds of sandy material would indicate a corresponding number of oscillations of the land, each elevation being marked with a revival of jungle or forest conditions.

The thickness of the strata between the different seams of coal affords some evidence of the duration of each subsidence; but the clay or stone-partings met with in many coal-seams cannot always be taken as an evidence of submergence. They may mark the encroachment of flood-waters on to the forest-lands during an abnormal inundation whereby a layer of mud was deposited among the vegetation, whose growth would be retarded but not destroyed.

Quality of Coals.—Coals enclosed in porous grits or sandstones are usually of inferior quality; while those interbedded with close-grained fireclays and compact sandstones are nearly always high class. The Upper Cretaceous system at Kaitangata, New Zealand, contains two coal-bearing horizons, a lower and an upper. In the lower horizon, which consists of loose quartzose sands and porous conglomerates, the coal is an ordinary lignite; while in the upper horizon, in which the seams are enclosed in thick beds of compact sandstone conglomerate, the coal is a hard bright coal of superior quality.

The quality of the coal is not dependent on the age of the enclosing rock.

Age of Coals.—Lignites are generally confined to the younger Tertiary formations. Brown coals are found in rocks ranging from the Cretaceous to Pliocene ; while true coals occur in all formations from the Cambrian to the Eocene.

The anthracite of County Cavan in Ireland is Silurian ; the true coals and anthracites of Great Britain, Continental Europe, and Pennsylvania, Carboniferous ; the coals of New South Wales and China, Carboniferous and Permo-Carboniferous ; and the semi-anthracites and bituminous coals of New Zealand, Eocene.

The brown coals of South Hungary, Transylvania, and North Germany are Lower Miocene ; of New Zealand, Upper Cretaceous and Lower Miocene : the lignites of Ireland are Pliocene.

All the greatest coal-deposits in the globe are of Carboniferous age, which would indicate that plant-life in this period reached a development and luxuriance unrivalled in any other geological age. The ferns, mosses, equisetums, lycopodiums, and lepidodendrons, which constitute the bulk of the Carboniferous coals, grew to a gigantic size, resembling in habit the forest trees of the present day.

Graphite.[1]—The ultimate phase of altered coal would appear to be represented by *graphite*, from which all the gases have been eliminated, only carbon and ash being left behind.

Lenticular beds of graphite, frequently associated with crystalline limestones, are found in Canada, Bavaria, Bohemia, New South Wales, interbedded with gneissic and schistose rocks of pre-Cambrian, Cambrian, and Silurian age. Graphite of fine quality is obtained from the Ordovician volcanic series at Borrowdale in Cumberland, and it is a constituent of graphite-slate, graphite-schist, and graphite-gneiss. Some of the Laurentian limestones of Canada are so charged with it as to be profitably mined for it.

Masses of graphite still adhering to the original sandstone are sometimes found among the detritus on the slopes of Mount Egmont, a volcano which has broken through the brown coal-measures of that part of New Zealand. This graphite has obviously arisen from the alteration of pieces of coal that became entangled or engulfed in the ascending floods of andesitic lava.

Graphite also occurs in veins and filling cavities, as well as in disseminated scales in granitic rocks in Ceylon, from which a large proportion of the world's supply is drawn. Scales of graphite have also been identified in basalt and diorite. Such graphite can hardly have had an organic origin.

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[1] Gr. *grapho* = I write, and *lithos* = a rock,

FERRUGINOUS ROCKS.

The rocks included in this group are chiefly important for their great economic value as ores of iron. They are usually limestones in which the carbonate of lime has been partly or wholly replaced by carbonate of iron. The oolitic iron-ore of the district of Cleveland in Yorkshire is a good example of this class of replacement deposit.

CHEMICALLY-FORMED ROCKS.

(*a*) Carbonates—Limestones.
(*b*) Sulphates—Gypsum.
(*c*) Chlorides—Rock-salt.
(*d*) Silica—Siliceous sinter.

The Carbonate, Sulphate, and Chloride deposits of this group are composed of granular or crystalline precipitates that frequently occur as lenticular sheets interbedded with sands, clays, and shales. They were deposited on the floor of saline lakes as a result of the evaporation and consequent concentration of the dissolved salts carried into the basin by the drainage of the surrounding country.

FIG. 116.—Deposit of travertine at a cascade.

The sediments of saline inland lakes seldom contain fossils except those carried into the basin by streams.

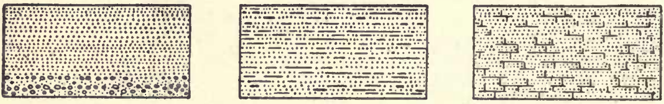
Carbonates.—Waters laden with the bicarbonate of lime or magnesia when they reach the open air part with carbonic acid, and the carbonates are at once deposited. *Travertine* or *Calcareous Sinter* is a soft spongy-looking carbonate of lime frequently deposited in rock-shelters and on hill-slopes in the form of rocky-cascades where the calcareous waters issue at the surface. These waters are popularly called *petrifying springs*, from the circumstance that the carbonate of lime is frequently deposited on ferns, crosses, twigs, and leaves, the forms of which are thus preserved.

Many travertines become hard and crystalline in structure through the deposit of secondary calcite.

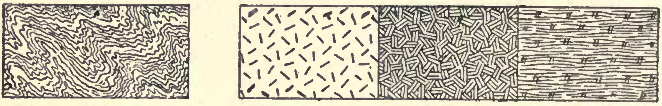
Dolomitic or magnesian limestones formed on the floor of saline lakes are not uncommon. The rock is often concretionary, granular, or finely crystalline in structure, and sometimes exhibits false-bedding. The precipitation of the mixed carbonates of lime and magnesia is partly due to the presence of sodium carbonate and partly to evaporation.

Sulphates and Chlorides.—In inland lakes that have no outlet to the sea, situated in regions where the evaporation about balances the flow of the incoming streams, the water in the course of time becomes charged with soluble salts. When a certain degree of saturation is reached, a portion of the salts passes out of solution and is deposited on the floor of the lake. In this way sheets of gypsum and rock-salt have been formed on the floor of the Dead Sea and Great Salt Lake. The basins of many of the saline lagoons in Central Australia and Utah are covered with a thick crust of rock-salt mixed with various impurities.

Limestones. Shales. Shaly limestones.



Sandstones and conglomerates. Shaly sandstones. Calcareous sandstones.



Schists. Massive and bedded igneous rocks.

Fig. 117.—Showing symbols used to represent different kinds of rock.

Deposits of gypsum are sometimes formed in volcanic regions. A striking example may be seen at White Island, New Zealand. Here the bed of the crater-lake is covered with a thick layer of gypsum deposited from the hot acid waters which fill the basin. The evaporation of the steaming water is rapid, but the loss is compensated by the mineral laden waters that issue from the steam-holes and hot springs around the margin of the crater.

Silica.—In regions of expiring volcanic activity, the thermal waters frequently carry a considerable amount of silica in solution in the form of soluble alkaline silicates which are easily decomposed by atmospheric carbonic acid. On reaching the open air the silica is deposited in the form of sheets and cascade-like streams. Extensive deposits of *siliceous sinter* occur in the volcanic region of New Zealand and in the Yellowstone National Park.

Conventional Symbols.

The symbols used by geologists to represent the more common rocks on maps are shown in fig. 117.

Summary.

(1) Sedimentary rocks, according to the character of the constituents, may be classified as *Detrital*, *Organic*, or *Chemical*.

(2) *Detrital* rocks are composed of sediments of various degrees of texture derived from the denudation of pre-existing rock-masses.

In *breccia* the material is angular; in *conglomerate*, water-worn and pebbly; in *sandstone*, sandy; and in *clays*, *shales*, and *slates*, very fine or clayey.

The cementing medium may be carbonate of lime, silica, oxide of iron, or a paste of sand and clay. The colour is generally determined by the degree of oxidation and hydration of the iron which is nearly always present.

(3) *Organic* rocks may be composed of animal or plant remains. They may be divided into four groups according to their composition, viz. *Calcareous*, *Siliceous*, *Carbonaceous*, and *Ferruginous*.

The *Calcareous* division comprises the limestones which consist of the calcareous shells and organisms of molluscs, corals, crinoids, and foraminifera. Some limestones, like chalk, are soft and earthy; others hard and massive, like the Belgian limestones; while many possess a granular or finely crystalline structure. Coralline limestones may develop a crystalline structure through the infiltration of calcareous waters; and by the replacement of a portion of the carbonate of lime with magnesium carbonate, the rock may be *dolomitised* or altered into a magnesian limestone or dolomite that may resemble the older dolomitic limestones.

Limestones may contain certain impurities. They may be clayey, forming an *argillaceous limestone* from which hydraulic cement is made, sandy, pebbly, or siliceous.

The *Siliceous* rocks of this group are *chert* and *flint*, mainly composed of *diatoms*—tiny plants that possess the power of extracting silica from sea-water.

The *Carbonaceous* rocks include all the known varieties of coal ranging from peat to anthracite.

The *Ferruginous* rocks are mostly carbonate of iron that has replaced the carbonate of lime in oolitic limestones.

(4) *Chemically-formed* rocks comprise carbonates, sulphates, chlorides, and silica. The last is deposited by hot springs in volcanic regions in the expiring or solfataric stage of activity; the others are deposited as precipitates on the beds of inland saline lakes. When the evaporation balances the inflow, the mineral matter carried into the lake in solution in time reaches a point of saturation, when precipitation takes place. In this way beds of *gypsum* and *rock-salt* have been deposited on the floor of the Dead Sea and Great Salt Lake.

CHAPTER XIV.

VOLCANOES AND VOLCANIC ACTION.

Definition of Volcano.—A volcano may be defined as a more or less conical elevation having a *crater* at its summit, from which steam, gases, streams of lava, dust, and scoriæ are ejected.

Volcanoes classified.—Volcanoes may be classified as :—

(*a*) **Extinct.**
(*b*) **Dormant.**
(*c*) **Active.**

An *Extinct* volcano is one which is not known to have been active within historic or traditional times.

A *Dormant* volcano is one which enjoys intervals of complete quiescence between the different eruptions, which may be separated by hundreds or even thousands of years.

Active volcanoes are always in a state of disturbance. Their paroxysmal outbursts are, however, generally intermittent and may be separated by long intervals of comparative quietude, during which the only evidences of activity are the emission of steam, and minor explosions that may give rise occasionally to showers of dust and *lapilli*.[1]

Examples :—

Extinct volcanoes,	. The craters of Auvergne in France, and Eifel in Rhenish Prussia.
Dormant volcanoes,	. Ruapehu and Tarawera, New Zealand.
Active volcanoes,	. Etna, Stromboli, Vesuvius, Hekla, Cotopaxi, Kilauea, Ngauruhoe.

This classification is not altogether satisfactory, as it is not always easy in its application. Historic time is so short relatively to the life of a volcano that the so-called extinct cone of to-day may be an active volcano to-morrow. Up to the time of its first known eruption in 79 A.D., Vesuvius was looked upon as extinct. Simi-

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[1] Ital. *lapilli*=little stones (mostly from the size of a pea to that of a small walnut).

larly Tarawera, which burst into activity with such startling suddenness in 1886, was never known to have shown the least sign of action before that date. It had suffered considerably from denudation and possessed no visible crater. The whole aspect of the mountain seemed to indicate a state of complete extinction of long duration.

Sites of Volcanoes.—The vent of a volcano may break through any geological formation, and may originate on the sea-floor, on dry land near the sea, on a plateau, or mountain-chain. The numerous volcanic cones of Auckland are piled up on a platform of Tertiary marine sandstones and clays not much above sea-level ; the Miocene volcanoes of Auvergne burst through the granitic and gneissic plateau of Central France.

Eruptions.—These may be of different types, as :—

(*a*) Volcanic eruptions = Vesuvian type.
(*b*) Fissure eruptions = Icelandic type.
(*c*) Explosive eruptions = Krakatoan type.

Vesuvian Type.— *Volcanic* eruptions are those confined to one crater or volcano, as at Vesuvius, Cotopaxi, and Egmont.

Icelandic Type.—In *Fissure* eruptions there is a quiet welling-up of lava along a line of fissure, accompanied with little explosive action and hence expelling little or no ash or fragmentary matter. The great volcanoes Kilauea and Mauna Loa in the Sandwich Islands are fine examples of the fissure type of volcanic action. The lava floods of Idaho, Victoria, Oregon, Washington, and California form plateaux over 200,000 square miles in extent ; and great basaltic plateaux also occur in Victoria, in Australia, and the Deccan in India. All have been formed by vast floods of lava that issued from fissure-rents of great magnitude.

The greatest outpouring of lava in historic times took place in Iceland in 1783. Floods of lava issued from a fissure twelve miles long and poured over the land, diverting streams from their course, filling up river-gorges, and forming lakes of molten rock on the neighbouring plains. The main streams travelled over forty miles from the point of emission.

Hekla does not form a cone, but an oblong ridge which has been split by a fissure along its whole length that bears a row of craters.

Krakatoan Type.—These take place through the sudden expansive force of subterranean steam. They usually happen with appalling suddenness ; and frequently their explosive force is so titanic that they rend and shatter the rocks at the point where the explosion is concentrated into fragments, which may be hurled far and wide with devastating effect. In a few hours forests may be destroyed, towns overwhelmed, lakes dried up, old land-marks obliterated, and the surrounding country converted into a lifeless desert.

The four most stupendous and destructive explosive eruptions of historic times are those of Vesuvius in 79 A.D., Krakatoa in 1883, Tarawera in 1886, and St Vincent in 1902.

Before 79 A.D., there was no tradition or record of former volcanic activity at Vesuvius. The ancient crater was overgrown with wild vines, while the mountain slopes and neighbouring plains were dotted with villages surrounded with vineyards and well-cultivated fields. At the base of the mountain stood the populous and cultured cities of Herculaneum and Pompeii.

The premonitory evidence of coming disturbance began with a series of earthquakes in 63 A.D., which caused much damage to buildings and created considerable alarm among the people living in the neighbourhood of the mountain. The earthquakes increased in frequency and violence, and in 79 A.D. finally culminated in a series of terrific explosions which truncated the bulk of the ancient cone by nearly one half, forming the well-known Monte Somma ring from which the present cone rises. The immense volumes of steam which issued from the crater were condensed and fell in torrential rains which swept down the mountain slopes carrying before them ejected dust and scoriæ. The floods of mud thus formed, together with the showers of falling ejecta, buried the cities of Herculaneum and Pompeii and devastated the surrounding country.

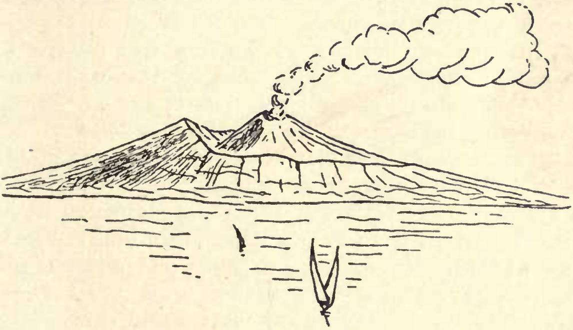

FIG. 118.—Vesuvius, showing the older crater-ring of Monte Somma and the new cone within it. (After Phillips.)

The history of Vesuvius, until the eruption of 1036, was a long series of explosive outbursts, producing only fragmentary material. In that year there was an overflow of lava for the first time ; and from then onward the mountain entered on a new phase of volcanic activity.

Perhaps the most stupendous explosive eruption in historic times was that which took place at Krakatoa, a volcanic island in the Straits of Sunda, between Java and Sumatra, in August 1883, when a large portion of the island was destroyed and the remainder devastated with a thick covering of dust and other fragmentary ejectamenta. The actual sound of the explosions was heard at Ceylon, more than 2000 miles away; and much of the dust was projected so high into the air and was so excessively fine that it was caught up in the upper currents of the atmosphere and carried many times round the globe, giving rise to a series of gorgeously coloured sunsets that continued for several months.

Particles of Krakatoan dust fell in Japan and America, and some even reached as far as Europe.

The disturbance in the surrounding sea was relatively greater than on land. The waves propagated by the explosions caused enormous loss of life on the adjacent coasts and low-lying islands. They travelled as far as Cape Horn, 7818 miles away.

The Tarawera eruption in New Zealand took place in June 1886, and was preceded by little or no warning. In a few hours after the first terrific outburst, the mountain and plateau at its base were rent with a gaping fissure nearly nine miles long. The volcanic energy soon became concentrated in numerous independent centres of explosive activity along the fissure from which there issued continuous showers of fragmentary matter and enormous volumes of steam. The dust was spread over 10,000 square miles, overwhelming the neighbouring forests and native villages, and converting the country into a weird grey wilderness. Immense volumes of steam were condensed into rain which, uniting with the falling dust, formed a plastic mud that broke down the forest-trees and buried the hapless villages lying in the track of the powerful winds that accompanied the eruption.

The sounds of the explosions were heard at Christchurch, over 400 miles away. They resembled the detonations of cannon or violent blows on the side of an empty iron-tank. It was during this eruption that the far-famed Pink and White Terraces at Rotomahana were destroyed.

The disastrous explosive eruption of Mon Pelée in Martinique is still fresh in the memory of everyone. In April 1902, the volcano began to emit steam, ashes, and sulphurous vapours. The latter were so abundant that horses dropped dead in the streets of St Pierre, situated on the plain bordering the mountain. On 5th May, floods of mud descended from the crater where it had been accumulating for some time, and earthquakes were numerous. On 8th May, the eruption reached its climax. On that day a black cloud of dust, steam, and sulphurous vapours swept down through the breach in the crater fronting St Pierre, passed over the plain, and in two minutes struck the city, which was at once overwhelmed, and the inhabitants to the number of 30,000 were killed. The detonations of the explosions that followed were heard 300 miles away.

The great crater of Mon Pelée is now occupied by a fragmental cone which terminates in a column of solid lava several hundred feet high. This column is believed to be the lava which solidified in the vent and was pushed up by the expansive force of the steam and vapour below.

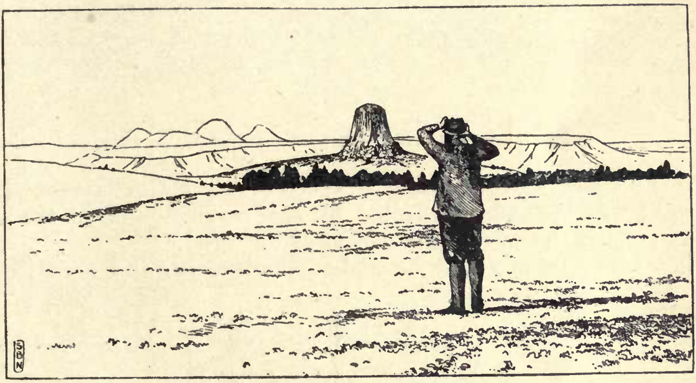

Fig. 119.—Showing plug of phonolite lava, Mato Teepee, Missouri, *U.S. Geol. Surv.* (After Jagger.)

Craters.—The crater[1] of a volcano is a cup-shaped depression at the summit which communicates below with a fissure in the Earth's crust. It is through this vent or pipe that the ejecta and gases issue from below.

Active and dormant volcanoes as a rule possess well-defined craters. In extinct volcanoes, older than Miocene, the craters and vents are generally obliterated by denudation ; but scores of craters in the Auvergne and New Zealand, that probably date back to the Miocene or early Pliocene, are as fresh as if only recently formed.

Volcanic Cones.—The fragmentary material and lava streams ejected by volcanoes accumulate around the neighbourhood of the vent, and thus build up the cone-shaped elevations that are so characteristic of volcanoes. At Auckland, where some of the cones have been cut down for the extraction of building-stone, the different

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[1] Gr. *krater* = a large bowl.

layers of material are seen to dip away from the central vent in all directions, as shown in the next figure.

Tuff-Cones.—These are volcanic cones composed of dust and scoriæ piled up by different eruptions. Frequently the material is spread out in distinct layers that may in some cases present the appearance of well-stratified aqueous strata. This arises from the fine and coarse material being arranged in alternating layers. The sorting was apparently effected by the varying force of the explosions and the winnowing action of the wind.

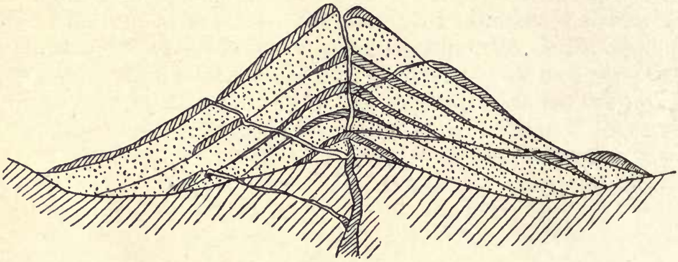


FIG. 120.—Showing structure of volcanic cone.

The structure of a tuff- or cinder-cone is shown in fig. 121.

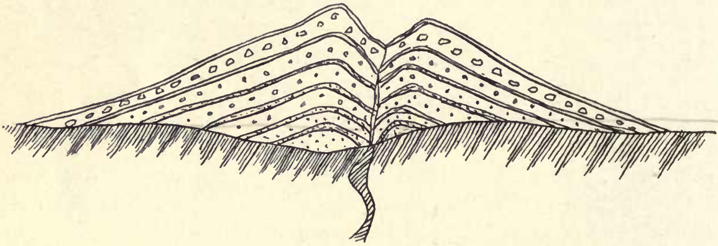


FIG. 121.—Showing structure of a tuff-cone with alternations of fine and coarse ash.

Lateral Cones.—In some of the larger volcanoes, the eruptions of lava do not always take place from the central crater at the summit, but from smaller vents on the sides. The uprising lava in the central fissure exerts enormous pressure on its walls; and in the case of a high volcano, rupture may take place at some weak point before the lava has risen high enough to overflow the crater-lip.

The fluid pressure of a column of molten rock with a specific gravity of 2·65 is 114·75 lbs. per square inch for every hundred feet of height, or 72 tons per square foot for every thousand feet. When the crater-walls are unable to withstand this pressure, rupture takes place at the weakest point.

The summit-crater of Etna is nearly always in a state of mild activity, emitting clouds of steam and dust, but the eruptions of lava usually take place from lateral vents around which there have been built small *parasitic cones*, ranging from 200 to 600 feet high.

Lava Streams.—When a stream of lava issues from a vent, it glows with a white heat, and at night may light up the sky overhead with a ruddy glow, as of a forest fire. It flows with the motion common to all viscous fluids, its rate of flow depending on the fluidity and depth of the mass, the steepness of the declivity, and the roughness of the ground over which it descends.

The upper surface, as it cools, assumes a red heat, and finally becomes black and cindery, the last effect being due to the escaping steam and gases which are expelled during the process of cooling.

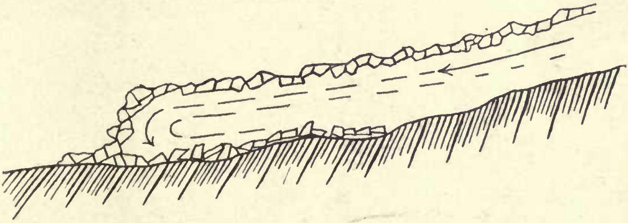


FIG. 122.—Showing mode of progression of lava stream.

The onward motion of the fluid mass below breaks up the solid surface into jagged, cindery, ragged cakes that are tilted up and frequently half engulfed in the molten flood below. Moreover, the rolling motion of the stream tends to pile the solid jagged masses into irregular mounds that are slowly carried forward on the moving tide of lava.

The front of the lava stream progresses by a rolling motion, by which the upper surface becomes the lower. In this way, before the stream has travelled far, the bottom has become a confused tangle of angular blocks that are slowly dragged along by the pasty mass.

The upper surface of very fluid lavas frequently becomes spongy and frothy, while the slowly cooling mass below assumes the curious ropy and streaky appearance of boiled sugar that has been poured down an inclined plane. The plane of this *flow-structure* is always parallel to the surface over which the lava travels, but accidental obstructions may cause the fluxion-planes to become bent, twisted, or gnarled.

In many volcanoes the lava rises up and fills the crater, over the rim of which it flows in a gentle stream; but when any portion of the crater-wall is weak, it may be carried away. The craters of Stromboli, Vesuvius, Ruapehu, White Island (Plate XVI.), and many other volcanoes have been breached in this way.

The molten lava, as it pours out of the vents, resembles the slag of a blast-furnace. When it cools rapidly, as it frequently does, at the thin edges of the stream, or where it flows into a sheet of water, it sometimes solidifies in the form of a glass.

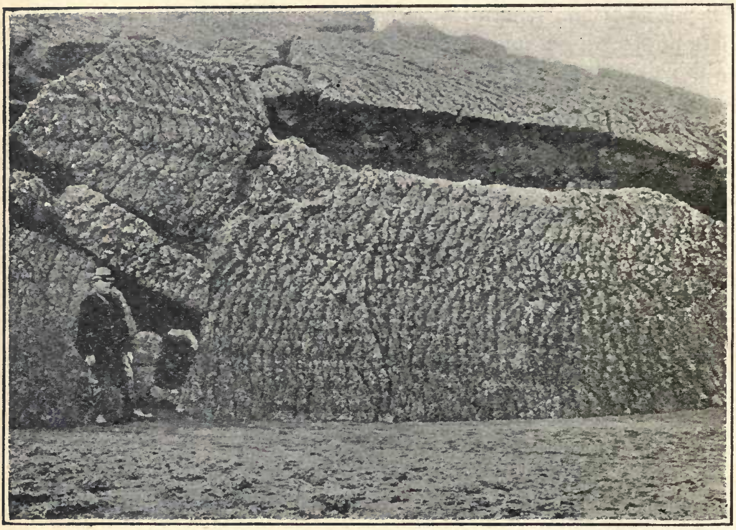
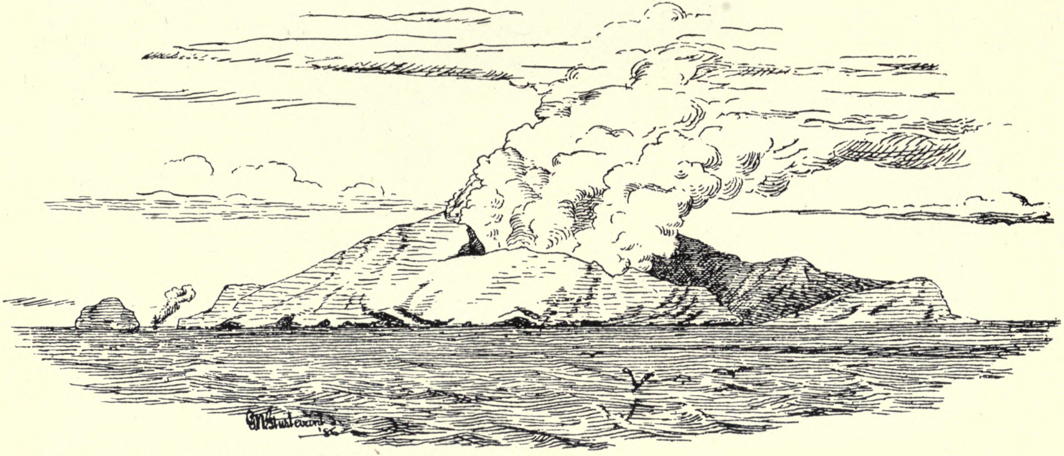


FIG. 123.—Showing corded structure of lava, Galtalaekr, Hekla, Iceland. (After Tempest Anderson.)

The vitreous or glassy form of acid lavas is called *obsidian* or simply *volcanic glass*; and the black, glassy form of basic lavas, *tachylite*. *Pumice* is the light, frothy, fibrous, spongy glass which forms on the surface of acid lavas. In other words, it is the cindery form of obsidian, and is frequently composed of a matted mass of glassy fibres.

Columnar Structure.—This structure is frequently seen in effusive rocks. It is developed by the stresses that arise in a thick stream of lava as it passes from the liquid to the solid state. As the result of the cooling and shrinking, the crust of the lava becomes

To face page 226.] [PLATE XVI.



From a Sketch by Mrs C. Alma Baker.]

WHITE ISLAND, NEW ZEALAND. LOOKING NORTH-EAST—THREE MILES DISTANT

intersected with more or less symmetrical sets of cracks that divide the surface into hexagons that fit one another like the cells of honeycomb. As the pasty mass under the crust cools, the cracks extend downwards at right angles to the surface. In a few cases the columns are arranged in a radial or fan-shaped form.

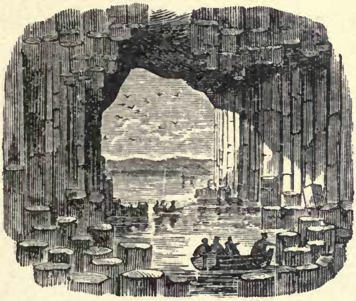


FIG. 124.—Fingal's Cave, Staffa.

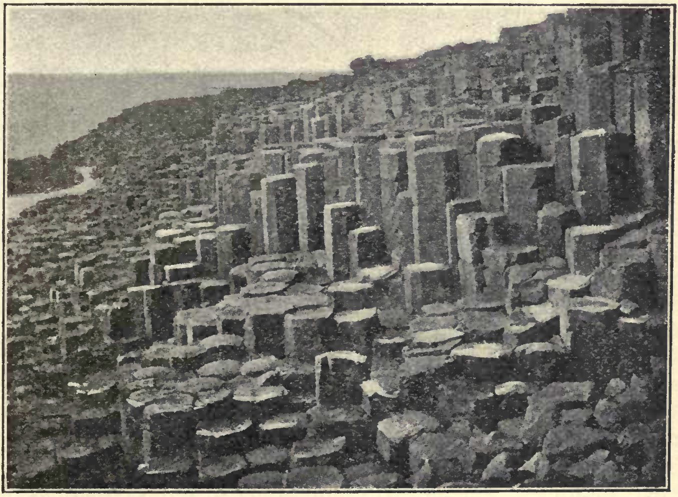


FIG. 125.—Showing columnar structure of basalt, Giant's Causeway, Antrim, N. Ireland. (After Tempest Anderson.)

Columnar structure, being mainly a result of contraction arising from cooling, is usually best developed in those portions of the magma exposed to the cooling effects of the atmosphere, and of the rocky surface on which the lava rests. Hence, in thick lava-flows this characteristic structure may be only developed in the upper and lower portions.

The columnar structure is found in effusive igneous rocks of all kinds, but is most frequently seen in those of a basic type.

Pillow-Structure.—When a very fluid basaltic lava is chilled by contact with water, the surface sometimes assumes the appearance of a number of large pillows packed together. Pillow-structure is seen in lavas of all ages. Good examples may be seen in the sea-cliffs near Ballantrae,[1] in south-west Scotland, where a flow of basalt is intercalated with the Silurian rocks; at Cape Oamaru,[2] New Zealand, where a stream of basalt is associated with Middle Tertiary strata; and on the sea-coast of Savaii, where the recent lavas of the Matavanu volcano flow into the sea.

Dr Tempest Anderson,[3] who was an eye-witness of the actual formation of this exceptional lava-structure, states that the lava, chilled by the waves, extended itself into lobes which, reduced to a pasty condition by cooling, would be seen to swell into buds with narrow necks, and these, being still in communication with the source of supply, would rapidly increase in heat, mobility, and size until they became lobes as large as a sack or pillow, or perhaps stopped short at the size of an Indian club or large Florence flask.

At Ballantrae and Cape Oamaru, the spaces or cracks between the pillows are filled with fossiliferous limestone.

Spheroidal Weathering.—Rocks are frequently divided by two systems of joints, or by joints and the bedding-planes, into roughly cuboidal blocks. When water percolates along these planes, it decomposes the rock, changing it into clay. At the edges where two planes meet the action is twice as rapid as on the sides of the block; and at the corners where three planes meet, it is three times as rapid. This differential rate of weathering causes the edges and corners to become gradually rounded, and in time the block may assume a spheroidal form.

When the decomposition of the block is complete, as frequently happens near the surface of the ground, the rock is entirely changed into clay; but when incomplete, a rounded, boulder-like core of undecomposed rock may remain in the centre.

The rocks that are the most prone to *spheroidal weathering* are basalts, andesites, phonolites, granites, tufaceous sandstones, and

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[1] B. N. Peach and J. Horne, *The Silurian Rocks of Scotland*, vol. i.; London, 1903.

[2] J. Park, "Marine Tertiaries of Otago and Canterbury," *Trans. N.Z. Inst.*, vol. xxxvii. p. 513.

[3] Tempest Anderson, "Volcano of Matavanu in Savaii," *Quart. Jour. Geol. Soc.*, vol. lxvi. p. 633.

[*To face page* 228.

FIG. 126.—Showing pillow-structure at Cape Oamaru, New Zealand.

greywackes; but such relatively soft rocks as mudstones and marly clays, that have been broken into small cuboidal blocks by shrinkage cracks, frequently exhibit this phenomenon in a perfect manner.

The clays resulting from the decomposition of rocks *in situ* are called *residual clays* to distinguish them from glacial clays, and the detrital clays that often accumulate on slopes and in hollows.

Spheroidal weathering is not always the result of aqueous decomposition. In regions where there is a considerable range of daily temperature, as in alpine valleys and arid highlands, angular blocks exposed at the surface soon assume a spheroidal shape. In this case the rounding is due to the stresses arising from the alternating expansion and contraction of the surface skin of the rock. If the intensity of stress on the sides of the block is represented by 1, that along the edges will equal 2, and at the corners or solid angles, 3. Owing to the action of these unequal stresses the block peels off in wedge-shaped flakes and curved splinters, and the effect of this is to cause the block to assume a rounded shape, but without the formation of residual clays.

Amygdaloidal Structure.—A lava stream, through the expansive force of the escaping steam and gases, is usually made vesicular or scoriaceous at the surface and bottom. Later these bubble-cavities may become filled with mineral matter deposited from solution, constituting what is called an *amygdaloidal structure.* The amygdaloids or almond-shaped blebs are obviously of *secondary origin.*

Fragmentary or Pyroclastic[1] Ejecta.—These rocks include the various fragmentary material ejected by a volcano, in the form of large and small *blocks*, *scoriæ*, *lapilli*, *ash*, and *dust.*

The *blocks* are mostly angular or subangular masses of lava that are often of enormous size. Rounded blocks are not at all rare. Among the blocks that are projected into the air many fall back into the throat of the vent, where they are churned up until again expelled. In this way the blocks that are not reduced to small fragments may be worn until they become well-rounded.

The cindery pieces of lava are called *scoriæ*; while the smaller scoriaceous fragments are usually spoken of as *ash.* The grit and dust are merely comminuted lava.

The small pieces of lava torn from the pasty lava form what are called *lapilli*, which range from the size of peas to that of walnuts. The larger masses of liquid lava that are projected from the vent solidify while swirling through the air, and thereby frequently assume a torpedo or bomb-like form with curious twisted ends; hence their name *volcanic bombs.*

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[1] Gr. *pur* = fire, and *klastos* = broken,

The coarse angular blocks, when consolidated, form what is called a *volcanic breccia.* The pell-mell mixture of large and small blocks set in a matrix of grit and dust, is usually called a *volcanic agglomerate.* The loose material that blocked up the throat of an expiring or spent vent forms, when consolidated, an *agglomerate-neck.*

The finer material ejected by volcanic explosions is frequently subjected to a certain amount of wind sorting, and hence is frequently deposited in layers that often possess a well-stratified appearance. The successive layers of material ejected by different eruptions form parallel sheets that, when exposed in gorges or on the banks of streams, appear to be stratified. Such bedded material is called *volcanic tuff.*

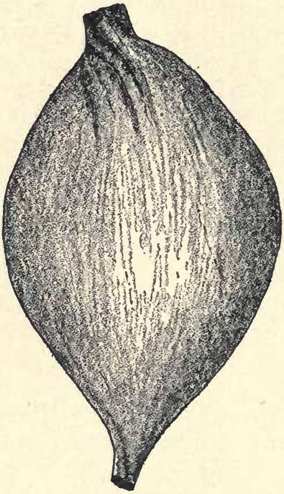
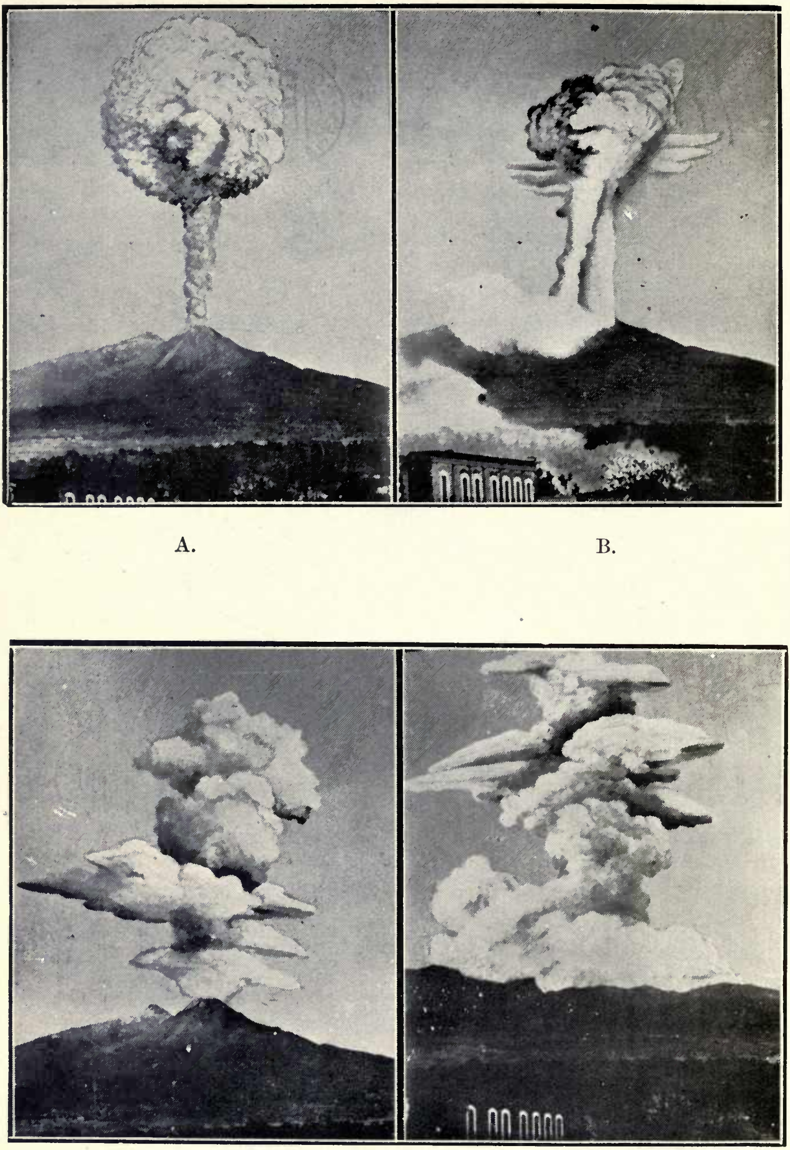


Fig. 127.—Showing volcanic bomb from Auckland, New Zealand.

Most volcanoes occur near the sea, and many are actually situated on the sea-floor. Lavas that flow into the sea are sometimes broken up into blocks and sand by the explosive action of the steam suddenly generated on their surfaces. The lavas and ashes of *submarine volcanoes* become interstratified with the ordinary sediments of denudation.

The ejecta from a land volcano may fall into the sea, or it may be carried into the sea by streams and rivers draining the eruptive area. When sorted and laid down in beds, this material forms what are called *marine tuffs.* Tuffs formed in this way may attain a



A. B.

C. D.

Cloud Forms—Eruption of Colimo Volcano, Mexico, 1910.
(Photographed from railway train during eruption.)

A. Form of steam cloud five minutes after first explosion.

B. At ten minutes.

C. At fifteen minutes.

D. At twenty minutes.

considerable thickness, but they will always be confined to the neighbourhood of the eruptive area. At their edges they may be interbedded with ordinary sandstones, mudstones, or limestones. Sandstones containing a considerable proportion of fine volcanic material are called *tufaceous sandstones.* Marine tuffs and tufaceous sandstones are frequently fossiliferous.

The fragmentary material ejected by a volcano frequently includes blocks of granite, schist, slate, or other rock torn from the rocks through which the volcanic fissure passes. Among the debris ejected by Vesuvius, blocks of fossiliferous limestone are comparatively abundant.

Steam and Gaseous Emanations.—The principal product of many volcanic eruptions is steam. In the early stages of the eruption the steam rises from the crater in the form of a pillar, which is crowned with a cloud shaped like a cauliflower ; in the later stages it spreads out into the well-shaped *pine-tree* form. These cloud-forms are well seen in Plate XVII., which shows an eruption of Colimo volcano, in Mexico, in 1910. The cauliflower cloud was seen to rapidly develop into the pine-tree form.

Besides steam, many other vapours, including those of sodium chloride, iron chloride, chlorine, sulphuretted hydrogen, and sulphurous acid, that were dissolved in the molten magma, escape from fissures and cracks in the cooling lava.

The exhalations in the first stages of cooling are mainly the chlorides of sodium and iron, and in the later stages sulphuretted hydrogen and sulphurous acid. In volcanic regions the characteristic smell of sulphurous acid, SO_2, pervades the atmosphere at all times, more particularly in regions where volcanic activity is on the wane.

The fissures from which gaseous emanations escape are called *Fumaroles*, the walls of which are frequently lined with beautiful incrustations of sulphur crystals sublimed by the interaction of H_2S and SO_2.

Expiring Volcanic Activity.—A volcano in the waning stage of its existence may emit only steam and various gases. The well-known decadent volcano Solfatara, near Naples, emits only steam and gases ; hence any volcano in this phase of activity is said to be in the *Solfataric* stage.

Thermal Springs.—In some regions of waning volcanic energy, the old craters are honeycombed with underground passages from which openings rise to the surface, where they generally terminate in basins filled with clear bluish-green mineralised waters, the majority of which are hot or boiling furiously.

The basins are generally situated on the summit of low mounds composed of siliceous sinter of various hues deposited by the over-flowing waters when they come in contact with the air. The largest groups of thermal springs are those of the Yellowstone National Park, U.S.A., and Rotorua, N.Z. At the latter region some of the springs are strongly alkaline, and others strongly acid. They all possess valuable therapeutic properties.

Geysers.—These occur in volcanic regions where the rocks, some little distance below the surface, are still intensely hot, and within the reach of springs or streams of water. They are connected by a fissure with a pool or basin from which the water at certain intervals is ejected with great force, frequently to a height of several hundred feet.

The principle underlying the intermittent action of geysers[1] is dependent on the expansive force of superheated steam. The fissure becomes filled with a column of water from the overflow of some neighbouring spring or stream. The heat is greatest in the lower part of the fissure; consequently the water in that part becomes hot, and soon reaches a temperature of 212° Fahr. The water would boil at that temperature at the surface, but owing to the hydraulic pressure of the column of water, it does not boil. On the contrary, it becomes hotter and hotter until in some portion of the fissure the boiling-point corresponding to the pressure is reached. The steam thus generated expands and pushes some of the water out at the surface. This relieves some of the pressure, with the result that the water below boils furiously. Steam is now generated with great rapidity, and, exerting enormous expansive force on the column of water, with a mighty roar, hurls it into the air together with any loose stones that may lie in its path.

Some geysers play at short intervals, while others are quiescent for days and even weeks. A geyser may be made to play before its customary time by the application of soap, which reduces the surface tension or strength of the resistant skin of water.

Distribution of Volcanoes.—If we look at a map of the globe, we are at once confronted with the significant fact that almost all recent indications of volcanic activity are to be found either along certain lines of coast or in islands. Most noticeable of all is the ring of volcanoes that fringes the great basin of the Pacific Ocean. This encircling girdle extends along the whole length of the Andes from Tierra del Fuego to Central America, whence it follows the coastal Sierras to the Aleutian Islands; from there passing southward to Kamtschatka, Kurile Islands, and Japan; thence stretching through the Philippines, Sumatra, Java, and adjacent islands to New Zealand.

Another remarkable zone of volcanoes girdles the globe from Central America eastward to the Azores, Canary Islands, Medi-

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[1] Ice. *geyser* = gusher or roarer.

terranean, Red Sea, and through a chain of islands to the mid-Pacific and New Zealand group.

Origin of Volcanoes.—It will be observed (*a*) that the distribution of active volcanoes is linear, and (*b*) that volcanoes rise either directly from the floor of the ocean or lie within a moderate distance from its coasts or of large sheets of water.

The linear distribution of volcanoes seems to warrant the inference that some connection exists between volcanic vents and crustal lines of weakness; while the coastal or oceanic situation of the vents leads to the further inference that eruptions are dependent on the presence of water.

Active volcanoes generally occur on the crests of terrestrial ridges, which supports the view that *ridges of elevation* resulting from folding are lines of crustal weakness. Further support of this contention is obtained from the gravity observations made in India and the United States. These observations show that mountain masses, such as the Himalayas, do not produce in the direction of gravity the effect that their visible mass should produce. In other words, they are deficient in density.

If the elevation of great earth flexures produces the initial lines of weakness, we cannot doubt that the immediate cause of volcanic activity is the expansive force of steam generated at enormous pressures from contact with heated rocks below. The origin of this magmatic water is still problematical. According to some, it finds its way below by seepage from the floor of the sea; according to others, it is *juvenile*—that is, an original constituent of the molten magma. Whatever its origin, its presence will render the magma more fluid, and since it must exist under enormous stress, it will cause the magma to penetrate every plane of weakness produced by the folding. Where the plane of weakness coincides with a ridge of elevation, we shall obtain a manifestation of the phenomena known as volcanic activity.

The great mountain-building folds of the globe are meridional, *e.g.* Andes and Rocky Mountains; or equatorial, *e.g.* Alps, Caucasus, and Himalayas; and it is only on the meridional folds or their prolongations that we find the evidences of crustal weakness as expressed by volcanic activity. The north and south chains are everywhere crowned with active volcanoes, while the east and west chains are singularly free from volcanic phenomena.

Former Volcanic Activity.—Piles of volcanic rocks are found interbedded with stratified formations of nearly all ages, and so far as we can form an opinion, the various types of eruption and the character of the lavas, dust, scoriæ, and other solid ejecta did not differ from those of the present day.

Some of the outbursts that took place in the Middle and Older

Palæozoic eras were on a stupendous scale, and have only been paralleled by those of the Middle Tertiary.

In the Mesozoic era, there was a singular, almost world-wide, interval of quiescence; but with the close of the Cretaceous, there came a remarkable revival of activity which probably attained its greatest intensity in the Miocene. Since then volcanic outbursts have become less and less violent, and narrower in their radius of disturbance. It would almost appear as if we were now living in a period of volcanic decadence.

The Lower and Middle Palæozoic and the Middle Tertiary were the great mountain-building periods of the globe, and also of maximum volcanic activity. The coincidence may be more than accidental, and may be additional evidence of the relationship of orogenic folding and volcanic activity.

Intermittent Volcanic Activity.—The piles of volcanic material that occupy some regions were not, as a rule, ejected by one outburst, but represent the accumulations of many eruptions.

Take the Hauraki Peninsula in New Zealand as a typical example. There we have a region over 100 miles long and from 20 to 30 miles wide occupied by a vast pile of lavas, breccias, and tuffs that have now been eroded into a complex of rugged mountains and steep ridges.

The first eruptions took place in the Middle Tertiary, and were characterised by the emission of floods of andesitic lavas. Then followed a period of quiescence during which the surface of the lavas became decomposed into soils on which a forest vegetation soon established itself. Many large streams drained the slopes of the volcanoes and spread the eroded material on the adjacent lowlands, thereby forming swampy flats on which peat-bogs flourished until they attained a great depth.

The next eruptions were mainly characterised by the ejection of fragmentary material. The forests were destroyed and the peat-bogs covered with thick sheets of ashes intercalated with streams of andesitic lavas.

During the period of cessation that followed, the land again became subject to denudation, and forests once more covered the land.

In the Pliocene there took place a vast outpouring of acid lavas which destroyed all vegetation and filled up the eroded contours. Since then there has been a complete cessation of all volcanic activity in the Hauraki area.

Old Land-Surfaces.—The old land-surfaces that existed between the different periods of activity can easily be traced in sea-cliffs and river-gorges. The layers of soil are usually baked and oxidised into reddish brick-coloured clays in which the remains of trees are found, in places converted into charcoal, or silicified into wood-opal, while the peat-bogs have been converted into lignite.

The old land-surfaces that mark periods of quiescence between successive eruptions can be detected in many volcanic regions. The seams of lignite and beds of shale interbedded with the Tertiary volcanic rocks of the Isle of Mull and Hauraki are a record of denudation and vegetable growth during a considerable cessation of volcanic activity.

SUMMARY.

(1) Volcanoes may be classed as *Extinct*, *Dormant*, or *Active*.

(2) Volcanic eruptions according to their character constitute three well-marked types:—

Vesuvian type, *i.e.* eruptions from a central cone.
Icelandic type, *i.e.* eruptions from a fissure-rent.
Krakatoan type, *i.e.* explosive eruptions.

(3) Active volcanoes are distributed along the coasts of the sea or large sheets of water. They are frequently situated on terrestrial ridges.

The linear distribution of volcanoes, and their proximity to the sea, would lead to the inferences (*a*) that they occur along lines of crustal weakness; and (*b*) that water in the form of steam plays an important rôle in their origin and eruptive force.

(4) The solid material ejected by volcanoes is mainly lava and such fragmentary matter as blocks, scoriæ, ashes, and dust. The gaseous products, in addition to enormous volumes of steam, are sodium and iron chlorides, chlorine, sulphurous acid, and sulphuretted hydrogen.

(5) When the crater-walls are weak, the lava may escape at points where in time lateral cones are built up.

(6) There is abundant evidence of volcanic activity throughout the whole of geological time, particularly in the Early and Middle Palæozoic and Tertiary eras. In the Mesozoic there was an almost complete cessation of volcanic activity throughout the greater part of the globe.

(7) Solfataras, geysers, and hot springs are evidences of waning volcanic activity.

CHAPTER XV.

IGNEOUS ROCKS.

OCCURRENCE, PHYSICAL CHARACTERS, AND COMPOSITION.

AN igneous rock is one that has cooled from a molten condition.

The study of igneous rocks includes a consideration of the following points :—

(*a*) Mode of Occurrence.
(*b*) Texture.
(*c*) Composition.

Mode of Occurrence.—An uprising molten magma that issues from a vent or fissure and spreads over the surface is said to be *effusive*, and the portions that cool and solidify below the surface are called *intrusive*.

The *effusive* rocks that are extruded from a volcanic vent generally take the form of *streams* ; while those that issue from fissure-rents may form *streams*, or they may first fill up the inequalities of the ground over which they flow and eventually spread over the country as wide *sheets*. A succession of very fluid lavas issuing from a fissure may build up a plateau as large as a State.

The *intrusive* rocks are not seen until laid bare by denudation. Their form is dependent on the shape of the pre-existing fissures or cavities which they fill, or of the cavities which they open for themselves by their eruptive force. Commonly they appear (*a*) as more or less vertical sheet-like veins called *dykes* ; (*b*) as irregular sheets called *sills* or *intrusive sheets* that have been intruded along the bedding planes of stratified rocks ; or (*c*) as more or less dome-shaped masses called *bosses* that have solidified in huge caverns at a considerable depth below the surface.

Thus, in the various forms assumed by eruptive rocks we have the basis of a convenient morphological classification which embraces all kinds of igneous rocks :—

I. **Effusive.**—Streams and floods of lava.
II. **Intrusive.**—Dykes, Intrusive Sheets or Sills, and Bosses.

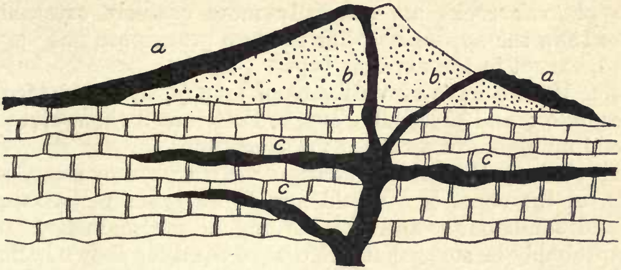

FIG. 128.—Showing lava streams and sills.

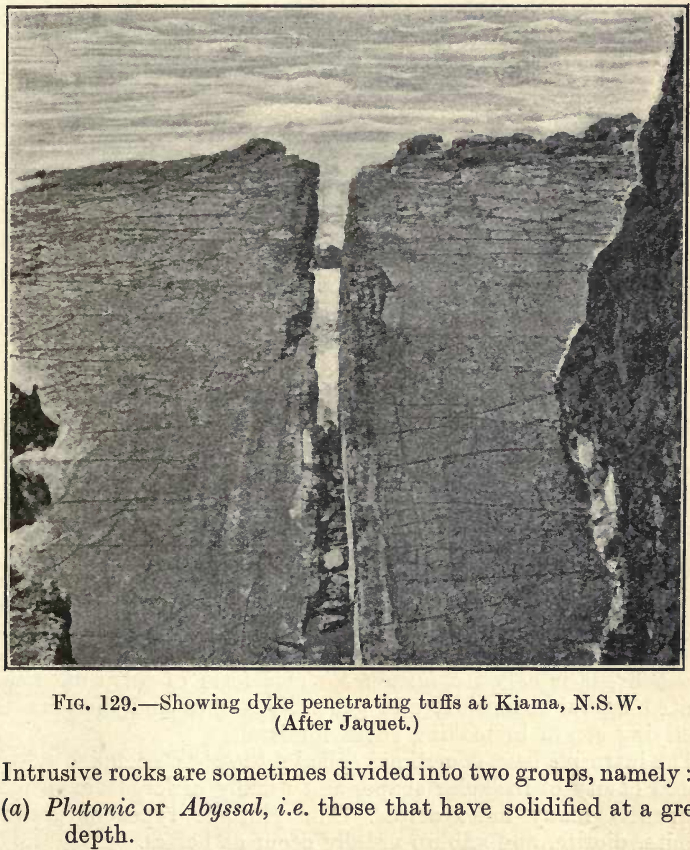

FIG. 129.—Showing dyke penetrating tuffs at Kiama, N.S.W. (After Jaquet.)

Intrusive rocks are sometimes divided into two groups, namely :—

(*a*) *Plutonic* or *Abyssal*, *i.e.* those that have solidified at a great depth.

(*b*) *Hypabyssal*, *i.e.* those that have solidified at a less depth.

The *plutonic* rocks are generally more coarsely crystalline in texture than the *hypabyssal*, but the two groups are not very well marked, except in the extreme types.

In fig. 128 we have two streams of lava, *a*, *a*, that issued from fissures, *b*, *b*, ; and three sills, *c*, *c*, *c*, that forced themselves along the bedding planes of a calcareous sandstone.

It is obvious that if denudation were to remove the greater portion of the cone, *b*, *b* would appear as dykes penetrating the tuffs and sandstone ; and the outcrop of the main dyke would not improbably be somewhat like that of the dyke shown in fig. 129.

Dykes, it should be noted, may vary from an inch or less to many thousands of feet wide. When the dyke-rock is harder and more resistant than the rock which it penetrates, it may be left standing above the general level of the ground as a conspicuous wall ; hence the origin of the name *dyke*. On the other hand, if softer than the enclosing rock, it may be worn away so as to expose the dyke-fissure, as shown in fig. 129.

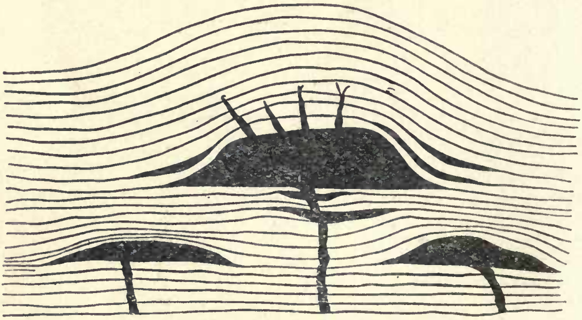

FIG. 130.—Showing dome-shaped sills or laccoliths.
(After Gilbert.)

When the magma rises through a pipe-like fissure, as it frequently does in volcanoes, the mass which solidifies in the pipe forms what is called a *volcanic neck*.

When a *sill* expands out to a dome-shaped mass lying between two beds, it is called a *laccolite*.[1] This form of intrusion has a limited lateral extension, and generally arches and disrupts the overlying strata in making room for itself.

The intrusive *boss*, sometimes called a *batholith*, occupies a deep-seated cavity of irregular shape, and usually of large dimensions, frequently many miles across. The plutonic types of granite, syenite, diorite, and gabbro usually occur as bosses.

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[1] Gr. *lakkos* = cistern, and *lithos* = stone.

Obviously, then, the self-same magma, according to the situation in which it cooled and consolidated, may be an *effusive* lava, or an intrusive *dyke*, *sill*, or *boss*.

Texture.—The texture of an igneous rock is not dependent on the composition of the original magma, but is mainly determined by the rate and conditions of cooling and consolidation.

The rate of cooling will mainly depend on the mode of occurrence of the eruptive magma. A lava stream, for example, will cool rapidly on the surface, at the selvages, and wherever it flows into a sheet of water. Moreover, a thin stream will cool more rapidly than a thick one. The magma that forms dykes and sills will cool more slowly than effusive lavas, and bosses more slowly than dykes. The relationship existing between mode of occurrence and texture is so intimate and well ascertained that when one of these is given, the other can be postulated within narrow limits of error.

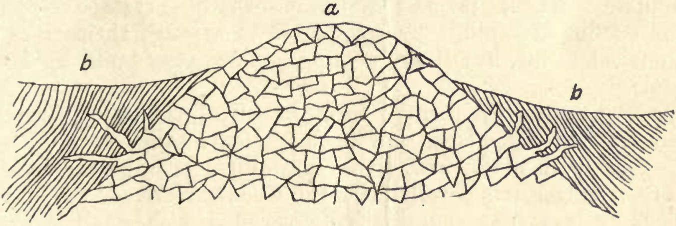

FIG. 131.—Showing intrusive boss exposed by denudation.
(*a*) Granite. (*b*) Slates.

Dykes and intrusive sills have cooled slower than lava streams, and more rapidly than bosses lying far below the surface. Moreover, dykes and bosses have not only cooled slowly but also under great pressure, the latter arising mainly from (*a*) the weight of the enclosing and overlying rocks, and (*b*) the internal stress of the imprisoned gases and steam occluded in the magma.

A molten magma does not differ from a furnace slag; hence, when it cools rapidly it forms a glass. When it cools slowly a crystalline structure is developed; hence, according to the rate of cooling, a given eruptive magma may present every variety of texture from the glassy to the completely crystalline.

A magma may become :—

(1) *Wholly glass* when it cools rapidly.

(2) *A glassy matrix* with a few small imperfectly formed crystals when it cools less rapidly.

(3) *A glassy matrix* crowded with large crystals when it cools slowly.

(4) *A matrix of minute crystals* with large crystals when it cools more slowly.

(5) *Completely crystalline*, i.e. *holocrystalline*, when it cools still more slowly.

A glass is a vitreous[1] body, and when it is partially crystallised, it is said to be *partially devitrified.* Devitrification is merely a process of crystallisation, and when the glass has been entirely replaced with crystals, it is *completely devitrified.*

The slower the rate of cooling, the more is the glassy matrix replaced by a crystalline structure, until a point is reached at which the ground-mass is wholly crystalline.

Generally speaking, the slower the cooling, the larger will be the crystals.

The incipient forms of crystals that first appear in a cooling glassy magma are minute rods and plates called *crystallites* or *microlites.*[2] These form the framework of crystal-skeletons. If the cooling is rapid, they are unable to arrange themselves in geometrical forms, but if the cooling is slow, they build up large crystals.

The crystallites frequently form beautiful radiating clusters. When grouped in spheres, they form what are called *spherulites.*

Frequently in glassy rocks the crystallites arrange themselves with their longer axis parallel with the *flow-structure.*

A glassy lava may sometimes be crowded with small enamel-like globules with an imperfectly developed concentric structure. This structure is called *perlitic*, and is not infrequently seen in acid lavas that have cooled more slowly than *obsidian.*

When conspicuous crystals of some mineral are enclosed in a finely crystalline ground-mass, the rock is said to be *porphyritic*, and the large crystals are called *phenocrysts.*

When a phenocryst is bounded by crystal faces, it is said to be *idiomorphic.*[3]

A rock in which the majority of the constituent minerals are idiomorphic is said to possess a *panidiomorphic* structure.

Should only some of the crystal faces appear, which is frequently the case with the minerals that are the first to crystallise after the phenocrysts, the structure is called *hypidiomorphic.*

In most holocrystalline rocks, owing to crowding and mutual interference, the minerals do not often assume geometrical forms, and are then said to be *anhedral*[4] or *allotriomorphic*, their shape being determined by their surroundings.

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[1] Lat. *vitrum* = glass.

[2] Gr. *micros* = small, and *lithos* = a stone.

[3] Gr. *idios* = distinct, and *morphe* = shape.

[4] Gr. *a* = without, and *hedron* = face.

FIG. 132.—Showing spherulites in a rhyolite.

FIG. 133.—Rhyolite showing flow-structure.

Fig. 134.—Showing perlitic structure.

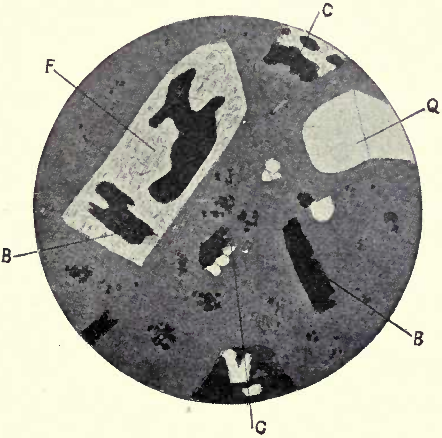

Fig. 135.—Showing porphyritic structure. (After Rumbold.)

F, Phenocryst of felspar altered to muscovite.
B, Biotite altered to cassiterite.
C, Cassiterite. Q, Quartz.

One mineral may penetrate another, and intergrowths of minerals are common, arising from simultaneous crystallisation.

Composition.—A rock magma may be defined as a solution of silicate-minerals; that is, of silica or silicic acid, SiO_2, combined with various oxides of the metals called *bases*. The bases with which silica combines most abundantly are:—

(1) Alumina = aluminium sesquioxide = Al_2O_3.
(2) Iron oxide = iron protoxide = FeO.
(3) Lime = calcium oxide = CaO.
(4) Magnesia = magnesium oxide = MgO.
(5) Soda = sodium oxide = Na_2O.
(6) Potash = potassium oxide = K_2O.

The great mass of igneous rocks is made up of a few minerals which are vastly more abundant than all the others put together. These few are *quartz*, the *felspar minerals*, the *ferro-magnesian minerals*, and the *iron oxides*, as under:—

Quartz, ...	As free silica.
Felspars, ...	Orthoclase, Monoclinic. Plagioclase, Triclinic.
Felspathoids, . . .	Leucite and nepheline, alkali minerals.
Ferro-Magnesian Minerals,	Pyroxenes, amphiboles, and micas.
Iron Oxides, . . .	Magnetite (Fe_3O_4) and hæmatite (Fe_2O_3). These occur as *free* or uncombined bases.

The leading pyroxene minerals are *augite, diallage, hypersthene,* and *enstatite.*

The principal member of the amphibole group is *hornblende.*

The most abundant *micas* are *biotite* (a black mica), and *muscovite*, a clear transparent variety.

The felspars are silicate compounds in which iron is absent. The ferro-magnesian minerals are silicate compounds in which iron plays an important part.

Chemical analysis shows the respective amounts of silica and bases present, and enables the following convenient grouping of igneous rocks to be made on a silica basis:—

I. **Acid Group,** with 65–80 per cent. of silica; and S.G. below 2·75. Typical rocks—Granites, rhyolites, felsites.

II. **Intermediate Group,** with 55–70 per cent. of silica; and S.G. between 2·70 and 2·80. Typical rocks—Diorites, andesites.

III. **Basic Group,** with 45–60 per cent. of silica; and S.G. between 2·80 and 3·00. Typical rocks—Gabbros, dolerites, basalts.

IV. **Ultra-basic Group,** with 35–50 per cent. of silica; and S.G. between 2·85 and 3·40. Typical rocks—The peridotites.

In each group the balance is represented by bases.

In the *Acid rocks* we have 65 per cent. of silica and 35 per cent. of bases. Thus it happens that there is more silica present than what is required to combine with the bases. The silica remaining uncombined after satisfying the bases is termed *free* silica, which appears in the rock in the form of quartz. Hence we find that all *acid* rocks contain a proportion of free silica or quartz.

In the *Intermediate rocks* the silica present about balances the bases; hence, in these, free silica is not often present; or, if present, it is generally in small amount.

In the *Basic* and *Ultra-basic* rocks, the bases predominate and free silica is absent.

Alteration of Igneous Rocks.—This is mainly effected by moist air, rain, or underground water containing carbonic acid and oxygen, or by thermal waters and acid vapours.

The crystalline minerals are hydrated, broken up, or replaced with other compounds. Among the first to break up are the felspars, which are converted into kaolin and mica. The felspars, when kaolinised, become cloudy, milky, and opaque.

Augite and hornblende become converted into calcite, chlorite, and magnetite; and olivine into serpentine.

The hydration and alteration of the felspars also gives rise to a very characteristic family of secondary crystalline minerals called *Zeolites*, which are mainly hydrous silicates of alumina and alkalies. The zeolites occur mostly encrusting or coating the walls of cavities, cracks, and veins in basalt, andesite, phonolite, and other volcanic rocks, and occasionally in granite and gneiss.

The more common zeolites are *natrolite*, *analcime*, *stilbite*, and *prehnite*.

The minerals that separate out of the molten magma are called *primary*, and those that result from the alteration or decomposition of the consolidated rock, *secondary*.

Secondary minerals are also introduced into a rock by infiltration. For example, the amygdaloids that fill the bubble-cavities in a vesicular lava are secondary.

Petrographical Provinces.—A petrographical province is part of a larger region in which the rocks exhibit certain points of resemblance due to some real genetic relationship or community of origin. It is easily conceivable that the lavas extruded from a common reservoir should be related, even though the points of emission might be far apart. The sympathetic action of Etna and Vesuvius would tend to strengthen the belief in the community of origin of magmas.

Magmatic Differentiation.—At one time it was believed that lavas were extruded in an orderly succession, beginning with acid rocks and ending with basic. Acid lavas were thought to characterise the earlier outbursts; intermediate lavas the maturer periods of activity; and basic lavas the expiring or waning phases.

All the lavas were believed to originate in a common stock-magma, and the different rock-types were supposed to be due to a process of magmatic differentiation. The idea probably originated in the supposition that the molten magma arranged itself in horizontal layers or zones of different density, the lighter acid glass forming the top layer and the basic the lower, like the charge from a blast-furnace, which separates itself into slag and regulus when poured into a mould.

Later investigation has shown that while this orderly succession of acid, intermediate, and basic lavas characterises many regions, the exceptions are so numerous that magmatic differentiation cannot be regarded as a law of effusion of general application.

The Atlantic and Pacific Types of Igneous Rocks.—The genesis of igneous magmas is still so obscure that all attempts to formulate a satisfactory genetic classification have ended in comparative failure, and the solution of the difficulty seems no nearer now than half a century ago.

Among the attempts in this direction, the Cretaceous and Tertiary igneous rocks have been divided into two main groups representing two great petrographical provinces, namely, *alkalic* and *calcic*, the former characterising the Atlantic type of coast-line, the latter the Pacific type.

Suess has advanced the postulate that alkalic rocks are typically associated with subsidence due to radial contraction of the globe; and the calcic with orogenic[1] folding arising from lateral compression. The volcanic islands scattered throughout the Atlantic are, he conceives, merely remnants of a once extensive tract of alkalic rocks now occupied by the Atlantic depression. On the other hand, the Pacific is fringed with a remarkable ring of andesitic rocks of the calcic type, and this encircling ring would seem to be connected with the uplift of the great crustal folds that girdle the Pacific coast-line.

The alkalic and calcic grouping has been extended so as to embrace the older plutonic rocks, the Atlantic group including the alkali-granites, nepheline-syenites, etc.; and the Pacific group the granites, quartz-diorites, gabbros, and norites.

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[1] Gr. *oros* = a mountain, and *genesis* = origin or creation.

In the main, the alkalic or Atlantic type of rocks occurs towards the Atlantic sea-board in both the American and Eurasian continents; and the calcic or Pacific towards the Pacific sea-board. Singularly enough, in Patagonia, where the Atlantic and Pacific come near one another, the types are curiously interwoven. In New Zealand, where we should look for the Pacific type alone, there is a curious commingling of the calcic and alkalic types in the small petrographical province of Otago Peninsula, on the east coast of the South Island; but in the greater petrographical provinces of Taranaki, Taupo, and Hauraki, in the North Island, the rocks belong to the Pacific group.

It is noteworthy that in the South Pacific Ocean, which is thickly dotted with groups of small islands in a way that would suggest a continental subsidence of the Atlantic type, the Hawaii, Tahiti, Cook, and other islands are largely composed of alkalic volcanic rocks.

Dr Flett has suggested a third group, the *spilitic suite*, consisting of the pillow-lavas and their associates occurring in the Dalradian schists of Scotland and in the Ordovician of the Southern Uplands of that country.

The alkali and the calcic types are *chemico-dynamic* rather than genetic. They are dominant elements in tectonics, and related to the development of certain crustal features, the origin of which does not, however, offer a satisfactory explanation of the genesis of the eruptive magmas. Moreover, they are conceived on too broad a basis to be adaptable for the requirements of a general classification of igneous rocks.

Classification of Igneous Rocks.—After nearly a century of investigation, no classification has been formulated that is generally accepted as a recognised standard, or that is satisfactory alike to the field-geologist and the laboratory student. The first attempts at classification were based on *megascopic* character—that is, on outward appearance of the rock, as seen in the field and in hand specimens. About the middle of the nineteenth century there came a better knowledge of the mineralogical characters of rocks, which soon led to a recognition of the prominent part played by the felspars. Since then the felspars have been an important factor in all modern classifications of igneous rocks.

The first great advance in petrography was the introduction of microscopical methods of investigation, the value of which was fully recognised before the advent of the seventies. The importance attached to this new branch of investigation was so overwhelming that for several decades there was a tendency among writers to place all other rock-characteristics in the background, and at one time there was a fear among field-geologists that the study of rocks would be altogether relegated to the laboratory. However, a reaction set in, and at the present time the importance of geological relationships, mode of occurrence, and formation are now recognised as no less important than mineralogical composition.

The classification of Rosenbusch, now widely adopted, divides igneous rocks into :—

(1) Deep-seated or abyssal.
(2) Dyke rocks or hypabyssal.
(3) Volcanic rocks or effusive.

This grouping is intended to express a relationship between mode of occurrence and texture. Genetically all three types of rock may originate from the same magma.

Zirkel bases his classification of igneous rocks on (*a*) *mineral character*, (*b*) *texture*, and (*c*) *age*.

English writers have always strongly combated the age distinction of igneous rocks, it being held that igneous magmas of similar composition are alike when solidified in similar conditions, regardless of the epoch in which they were erupted.

The *mode of occurrence* of igneous rocks is dependent on local or regional crustal weakness, as indicated by the presence of fractures and fissures, and on certain dynamic conditions, the origin of which is still obscure.

The *texture* is merely an expression of the mode of occurrence.

The *composition* is independent of both mode of occurrence and its concomitant texture. For example, the same magma, according to some accident of local crustal weakness, may occur as a boss, a dyke, an intrusive sill, or an effusive lava—four well-marked morphological types that may differ in texture, but not in composition.

The following arrangement of igneous rocks is based on texture and mineralogical character, and is useful as showing the succession of related rock-families as we pass from the acid to the basic.

Texture.	ACID.	INTERMEDIATE.		BASIC.
	Orthoclase.		Plagioclase.	
	Quartz.	Hornblende or Augite.		Augite or Olivine.
Glassy . .	Obsidian	Trachyte glass	Andesite glass	Tachylyte
Partly crystalline	Rhyolite	Trachyte	Andesite	Basalt
Holocrystalline .	Granite	Syenite	Diorite	Dolerite

An acid magma of uniform composition may give us a granite, rhyolite, or obsidian, according to the position in which it cooled and consolidated; and a basic magma, a dolerite, basalt, or tachylyte. The acid rocks differ in mineralogical character and texture, but not in chemical composition; this is also true of the basic and intermediate rocks.

The holocrystalline types of rock occur mainly as plutonic bosses, dykes, and laccoliths; the partly-crystalline principally as lava streams and sills; and the glassy generally as effusive lavas.

SUMMARY.

(1) The points that should be specially emphasised in connection with igneous rocks are :—

(*a*) Mode of occurrence.
(*b*) Texture or grain.
(*c*) Composition.

(2) The same uprising molten magma, according to the situation in which it cools and consolidates, may form :—

(*a*) An *intrusive boss* that penetrates the crust, crushing, disrupting, displacing, and perhaps even dissolving the rocks with which it comes in contact, but in no case reaching the outer surface.

(*b*) *Vein-like sheets*, called *dykes*, that fill fissures and cracks in the rocky crust.

(*c*) *Intrusive sills or sheets* that have forced their way along the bedding planes of stratified rocks.

A sill that has swelled out to a dome-shaped mass is called a *laccolith*. A large laccolith that is only partially uncovered is sometimes difficult to distinguish from an intrusive boss.

(*d*) An *effusive stream* of lava that issued from a vent or fissure.

(3) A molten magma is merely a natural slag or glass. When it cools rapidly it retains the glassy structure, but when it cools very slowly it develops a completely crystalline structure. Between the glassy and holocrystalline forms, we get an endless variety of rock-textures, varying according to the rate and conditions of cooling.

(4) A molten magma may be regarded as a solution of rock-silicates, and as it cools, the silicates separate out in crystalline forms. The principal constituents of igneous rocks are as under :—

(*a*) *Quartz,* occurring free or uncombined.
(*b*) *Felspars*—Orthoclase and Plagioclase.
(*c*) *Felspathoids*—Leucite and Nepheline, both alkali minerals.
(*d*) *Ferro-magnesian minerals,* a group of great importance, including the augites, hornblendes, micas, etc.
(*e*) *Iron oxides,* mostly magnetite and hæmatite.

(5) The alteration of igneous rocks is mainly effected by water containing CO_2 and O, and by thermal waters and various gases.

The products of the alteration of primary minerals are called *secondary* minerals.

(6) *Petrographical Provinces* are regions in which the rocks exhibit certain points of resemblance.

(7) *Magmatic Differentiation* refers to the succession of acid, intermediate, and basic lavas that was at one time believed to represent the normal sequence of magmatic effusions in a given volcanic region.

(8) The *Atlantic* or *Alkalic* and the *Pacific* or *Calcic* types of igneous rock represent two great petrographical provinces, the former characterising the Atlantic type of coast-line, the latter the Pacific type. These two groups of rock-types are believed to be related to the genesis of certain crustal features, the Atlantic group with depression, and the Pacific with orogenic folding.

Where the Atlantic and Pacific meet south of Patagonia, there is a singular commingling of the alkalic and calcic types of rock.

(9) No satisfactory basis has, so far, been discovered for a genetic classification of igneous rocks. Most modern classifications are based on *mode of occurrence, texture,* and *composition.*

Based on mode of occurrence alone, we get

(*a*) Deep-seated or abyssal.
(*b*) Dyke rocks or hypabyssal.
(*c*) Volcanic rocks or effusive.

The *Deep-seated* or plutonic rocks are holocrystalline, the dyke rocks mainly holocrystalline, and the volcanic rocks partly crystalline and glassy.

According to their composition, igneous rocks are divided into four main groups as follows :—

(*a*) Acid.
(*b*) Intermediate.
(*c*) Basic.
(*d*) Ultra-basic.

It must, however, be remembered that the study of rocks is more important than the formulating of a classification, the latter being of value only so far as it assists us in the systematic investigation of rock-masses.

CHAPTER XVI.

PLUTONIC, HYPABYSSAL, AND VOLCANIC ROCKS.

A.—**Plutonic Rocks.**

THE rocks of this type generally occur in bosses or boss-like protrusions that have evidently cooled at a considerable depth below the surface. Their presence is in every case revealed by the denudation of the overlying rocks; and their actual extent is never known. They are *holocrystalline*, and in general the crystals are imperfectly formed owing to mutual interference. The presence of water and gases in the crystals would tend to show that the process of crystallisation took place under great pressure.

The distinctive feature of these abyssal rocks is their coarsely crystalline texture.

Sequence of Crystallisation.—In plutonic rocks which from their deep-seated character have necessarily cooled very slowly, there has been recognised a normal order of separation for the crystalline constituents which, although not invariable, is sufficiently general to warrant the broad generalisation of Rosenbusch that the order of crystallisation follows a law of *decreasing basicity*, as follows :—

I. (*a*) *Minor accessory minerals* = Apatite, zircon, sphene, garnet; (*b*) *Iron ores* = Magnetite, hæmatite, pyrite.
II. *Ferro-magnesian minerals* = Olivine, hypersthene, enstatite, augite, hornblende, biotite, muscovite.
III. *Felspar minerals* = (*a*) Plagioclase; (*b*) Orthoclase.
IV. (*a*) *Quartz*; (*b*) *Microcline.*

It will be observed that the basic accessory minerals and iron-ores appeared before the ferro-magnesian minerals which play so conspicuous a part in plutonic rocks. After the complex silicates follow the great group of felspar minerals which are devoid of iron; and after these come quartz and, finally, microcline.

Varieties of Structure.—The principal textures met with in plutonic rocks are as under :—

(*a*) *Granitoid*, *i.e.* like that of an ordinary granite.
(*b*) *Granulitic*, *i.e.* consisting of small grains of even size, imparting a granular appearance.

(*c*) *Pegmatitic, i.e.* strikingly coarse-grained, as found in typical pegmatite.
(*d*) *Porphyritic, i.e.* where conspicuous phenocrysts occur in a ground-mass of small crystals.
(*e*) *Graphic,*[1] *i.e.* a structure depending on the intergrowth of two essential minerals, and so named from its resemblance to Hebraic writing. It commonly arises from the interpenetration of felspar by quartz. This structure is usually on a microscopic scale, and hence is often called *micrographic.*
(*f*) *Gneissic, i.e.* when the constituent minerals exhibit a tendency to aggregation in parallel bands, arising partly from the flowing movement of the parent magma, and partly from subsequent rearrangement due to pressure and heat.

Principal Plutonic Rock Types.

Plutonic	1. Granites	Acid.
	2. Syenites	
	3. Diorites	Intermediate.
	4. Gabbros	
	5. Norites	
	6. Peridotites	Basic.

ACID PLUTONICS.

Granites.—These consist of rocks in boss-like masses from which veins or dykes may extend into the adjacent rocks.

The colour of granite is mainly dependent on the hue of the felspar, and is usually light or dark grey, pink, or reddish. The felspar usually shows cleavage-planes or crystal faces, and is thereby easily distinguished from the quartz, which possesses no cleavage, and usually occurs in irregular grains. The mica occurs in thin flexible scales. Orthoclase is the essential felspar, but a little accessory plagioclase is nearly always present.

The leading types of granite are :—

(*a*) *Granite* = quartz, orthoclase, and two micas ; one muscovite mica, the other biotite.
(*b*) *Biotite-granite* = a granite in which the grey mica is replaced by the brown mica, biotite.
(*c*) *Hornblende-granite* = a granite in which the mica is wholly or partly replaced by hornblende.

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[1] Gr. *Grapho* = I write.

(*d*) *Pegmatite* = a strikingly coarse-textured granite which commonly occurs in veins in ordinary granite, or on the borders of granite bosses.
(*e*) *Greisen* = a granite with little or no felspar; occurs in veins in ordinary granite.

Fig. 136.—Photomicrograph of granite, near Dublin. × 12. (After Grenville A. J. Cole.)

(*b*) Brown mica (biotite).
(*m*) Muscovite, a hexagonal section of this mineral occurs near top of section.
(*o*) Orthoclase. (*q*) Quartz.

A normal granite containing tourmaline may be called a *tourmaline-granite.*

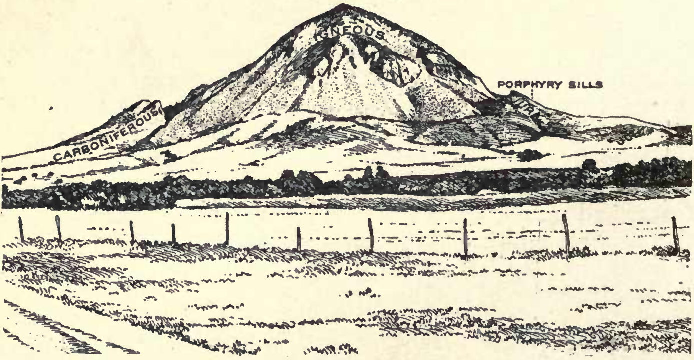

Fig. 137.—Showing Bear Butte Laccolith, Black Hill, S. Dakota, *U.S. Geol. Surv.* (After Jagger.)

When a granite contains conspicuous phenocrysts of felspar, it is said to be *porphyritic*, and in this case the rock may be called a *granite-porphyry*.

Many granitic rocks contain irregularly rounded or ovoid patches of a darker colour and finer grain than the enclosing rock. These patches are called *basic secretions.* They contain the same minerals as the parent rock, and are supposed to be the earlier products of crystallisation.

Syenites.—These are coarse to fairly fine-grained holocrystalline rocks with a granitoid structure. In a general way they may be defined as granites without free quartz. They occur in the form of bosses and dykes, but are much less common than granite. The leading types are as follow :—

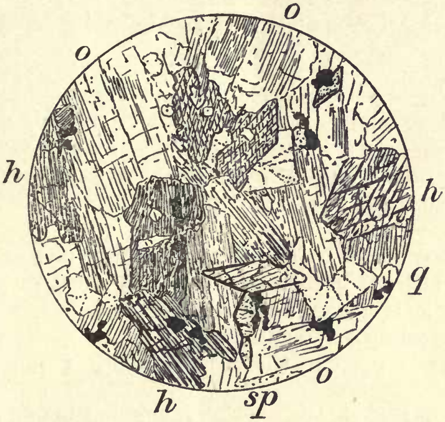

FIG. 138.—Showing syenite from Plauenscher Grund, Dresden. ×8.

(*h*) Green hornblende. (*q*) Accessory interstitial quartz.
(*o*) Orthoclase fairly prismatic in habit. (*sp*) Sphene.

(*a*) *Hornblende-syenite* = Syenite proper, composed essentially of orthoclase and hornblende.
(*b*) *Mica-syenite,* in which biotite more or less replaces the hornblende.
(*c*) *Augite-syenite,* an ordinary syenite in which augite is present.
(*d*) *Alkali-syenites.* These are syenites distinguished by the presence of nepheline or sodalite.

Plagioclase is present as an accessory constituent in all syenites. When it becomes a prominent associate of the orthoclase, we get types that show a relationship to the diorites. To this intermediate type the name *monzonite* has been applied.

Syenites containing quartz form a connecting link with the hornblende granites.

INTERMEDIATE PLUTONICS.

Diorites.—These are holocrystalline rocks of fine or fairly coarse texture. They consist essentially of plagioclase and hornblende. Free quartz is frequently present in them, but the influence of the basic felspar, oligoclase, or sometimes labradorite keeps the rock in the intermediate group.

The diorites generally occur as dykes, and they are found in all parts of the globe. The leading types are as under :—

(*a*) *Diorite*[1] = plagioclase + hornblende.
(*b*) *Mica-diorite* = plagioclase + hornblende + biotite.
(*c*) *Quartz-mica-diorite* = plagioclase + hornblende + biotite + quartz.

Gabbro Type.—These occur as dykes and large boss-like intrusions. They show a close relationship to the last group, and may be called *pyroxene-diorites.* They consist essentially of a plagioclase felspar (usually labradorite) and a pyroxene. When the pyroxene is augite or diallage, we get *gabbro* proper, and when hypersthene, *norite.*

Almost all the rocks of this group contain *olivine,* and in the more basic varieties it becomes an essential constituent.

Gabbro = plagioclase + augite or diallage.
Norite = plagioclase + hypersthene.

When quartz is present, the rock becomes a quartz-gabbro or quartz-norite.

Many of the basic gabbros are rich in magnetite and ilmenite, and some pass into *iron-ore* rocks, as in Minnesota.

BASIC PLUTONICS.

Peridotites.—These occur mostly as dykes in other basic rocks. They are holocrystalline in texture, and basic or ultra-basic in composition. They consist essentially of olivine, which may constitute 50 per cent. or more of the rock, while felspar is typically absent. Enstatite or bronzite is nearly always present, and, in some types, augite or hornblende. The leading types are :—

(*a*) *Enstatite-peridotite* = olivine + enstatite.
(*b*) *Augite-peridotite* = olivine + augite.
(*c*) *Hornblende-peridotite* = olivine + hornblende.

An olivine-rock containing a little chromite and magnetite forms mountain masses of great extent in New Zealand. It has received the distinctive name *Dunite,* so called after Dun Mt., where it is typically developed.

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[1] Gr. *diorizo* = I distinguish.

A. DIORITE, YELLOWSTONE NATIONAL PARK. (U.S. Geol. Survey.)

B. DIORITE-PORPHYRY WITH PHENOCRYSTS OF PLAGIOCLASE, YELLOWSTONE NATIONAL PARK. (After Iddings, U.S. Geol. Survey.)

[*To face page* 252.

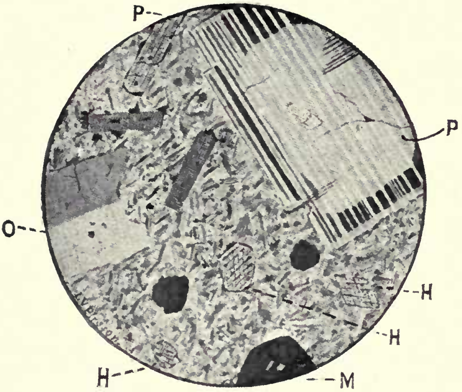

Fig. 139.—Micro-drawing of diorite-porphyry, *U.S. Geol. Surv.* (After Pirsson.)

P, Phenocryst of plagioclase with well-developed albite-twinning and distinct pericline-twinning.
O, Orthoclase. H, Hornblende. M, Magnetite.

Fig. 140.—Showing gabbro from Yellowstone National Park. (After Iddings.)

The olivine of the peridotites and dunite alters with great readiness into the hydrous form, *serpentine*.

B.—Hypabyssal Rocks.

The igneous rocks included in this group as a rule occur in the form of dykes, and are probably protrusions from deep-seated bosses.

Most of them are holocrystalline, and this texture is so general as to be characteristic. In some, however, there is a glassy residue.

Fig. 141.—Micro-drawing of peridotite, deeply serpentinised. × 70. (After Hartog.)

O, Olivine.
A, Antigorite, scale serpentine.
S, Serpentine apparently massive.
G, Garnet. Solid black, magnetite.

Dyke rocks, like the plutonics, are typically compact, but a few are known that possess a vesicular structure like a volcanic lava.

In some of the families of this group, the porphyritic structure is so constant as to be characteristic.

I. *Quartz-porphyry*—Acid.
II. {*Porphyries*, *Porphyrites*} Intermediate.
III. {*Lamprophyres*, *Dolerite*} Basic.

ACID GROUP.

Quartz-Porphyries.—These are also known as *felsites, quartz-felsites*, or *elvans*. They abound as dykes and veins in the neighbourhood of granite bosses, with which they are doubtless genetically related. Their colour varies from white to buff.

In the rocks of this family the ground-mass consists of a microcrystalline or crystalline aggregate of quartz and felspar, in which are embedded crystals of quartz and orthoclase, and frequently biotite or some other ferro-magnesian mineral. Mineralogically and chemically many of the varieties of this family are merely fine-grained granites or *micrograniles*, as they are sometimes called.

When the ground-mass is so fine that it is difficult to recognise the various constituents even under high powers, it is called *felsitic*.

The fine-grained and compact forms of granite frequently found traversing ordinary granites as narrow dykes, are called *quartz-felsite* in England, *microgranulite* or *microgranite* in Continental Europe, and are covered by the name *eurite*.

The fine-grained granites that consist only of quartz and orthoclase in a felsitic ground-mass, are sometimes called *aplite*.

Many of the so-called *felsites* and *quartz-felsites* are ancient rhyolites that have undergone some secondary changes.

INTERMEDIATE GROUP.

These are holocrystalline dyke rocks with a porphyritic structure, due in most cases to the presence of felspar phenocrysts. They are divided into two families, the *porphyries* and *porphyrites*;[1] the former is dominated with orthoclase, the latter with plagioclase. Thus, while the porphyries are related to the syenites, the porphyrites approach the diorites.

Porphyries.—The leading types of these are as follow :—

(*a*) *Orthoclase-porphyry* = orthoclase + a little biotite, hornblende, or augite.

(*b*) *Syenite-porphyry* = ground-mass of quartz and felspar, mostly orthoclase; phenocrysts, plagioclase + hornblende.

Porphyrites.—The leading types of these are :—

(*a*) *Hornblende-porphyrite* = plagioclase + hornblende + biotite.
(*b*) *Mica-porphyrite* = plagioclase + biotite.

BASIC GROUP.

Lamprophyres.—This is a peculiar family of basic dykes typically found traversing rocks of older Palæozoic age. They are fine-grained and essentially holocrystalline. They are peculiarly rich in the ferro-magnesian minerals, biotite, hornblende, or augite.

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[1] Gr. *porphura* = purple, and *lithos* = a stone.

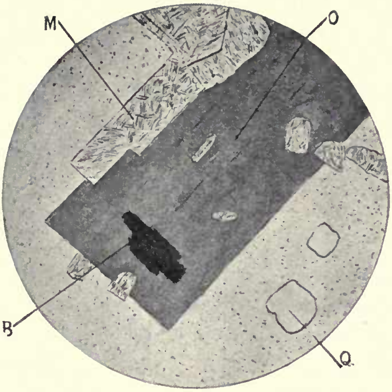

FIG. 142.—Micro-drawing of quartz-porphyry from Mariana Mine. Tres Cruces. Ground-mass felsitic. (After Rumbold.)

O, Orthoclase. M, Felspar altered to muscovite.
B, Biotite. Q, Quartz.

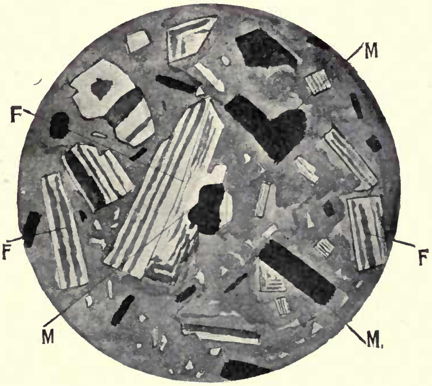

FIG. 144.—Micro-drawing of Negro Pabellon mica-andesite. (After Rumbold.)

Ground-mass, Glass. M, Mica altering to magnetite. F, Plagioclase felspar.

The felspars, which may be orthoclase or plagioclase, occupy a subordinate place. Olivine is absent or sparingly represented. In some the silica is as low as 40 per cent.

The various types take their name from the dominant ferromagnesian mineral Thus we have :—

(*a*) *Hornblende-lamprophyre,* with dominant plagioclase = *camptonite* type.
(*b*) *Mica-lamprophyre.*
(*c*) *Augite-lamprophyre.*

In the monchique type of lamprophyre, the characteristic minerals are olivine + augite, or sometimes hornblende.

Dolerites.—These occur as laccoliths, sills, and dykes. They are holocrystalline, but not conspicuously porphyritic. The leading types are as under :—

(*a*) *Olivine-dolerite* = plagioclase + augite + olivine.
(*b*) *Mica-dolerite* = plagioclase + augite + biotite.
(*c*) *Hornblende-dolerite* = plagioclase + augite + hornblende.
(*d*) *Enstatite-dolerite* = plagioclase + augite + enstatite.

The more ancient dolerites have generally undergone considerable alteration to a greenish-black rock, to which the distinctive name *diabase* has been applied. The greenish colour is due to the chloritic decomposition products. The principal varieties are as follow :—

(*a*) *Diabase* proper = plagioclase, mostly labradorite + augite.
(*b*) *Olivine-diabase* = plagioclase + augite + olivine.
(*c*) *Quartz-diabase* = plagioclase + augite + quartz.
(*d*) *Hornblende-diabase* = plagioclase + hornblende.

Many of the Palæozoic diabases are conspicuously amygdaloidal, notable examples being the copper-bearing diabases of Lake Superior, and the great sheet of diabase overlying the gold-bearing *banket* series at the Rand.

C.—**Volcanic Rocks.**

In this group are included all the solid effusive lavas as well as the dykes and sills that are directly connected with lava streams. They range from the glassy to the holocrystalline forms. The glassy structure is most prevalent among the acid types of rock.

Volcanic rocks are frequently vesicular, and usually exhibit flow phenomena such as flow-lines, parallel orientation of crystals, elongation of bubble-vesicles, and banding. The majority exhibit a porphyritic structure, due to the presence of two generations of crystals. The large felspars separate out of the slowly uprising glassy magma, and, being free from crowding or interference, generally grow to a large size.

At a later stage of the eruption, probably after effusion of the magma as a lava-stream, the separation of the second crop of felspars begins; and the rate of cooling being more rapid than before, the crystals are small and often crowded.

With the volcanic rocks, as with the plutonic and hypabyssal, we have the threefold division, based on chemical composition as under:—

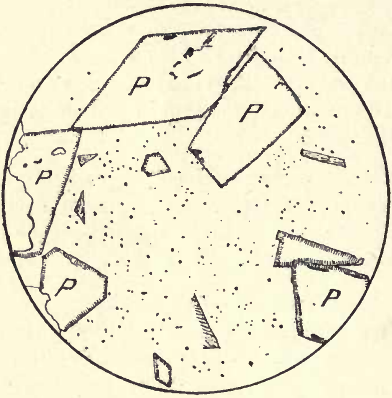

Fig. 143.—Showing phenocrysts of plagioclase in glassy ground-mass, *U.S. Geol. Surv.*

I.	*Rhyolites*—	Acid.
II.	*Trachytes* *Phonolites* *Andesites*	Intermediate.
III.	*Basalts*—	Basic.

Acid Group.

Rhyolites.—These include all the more acid lavas of Recent and Tertiary date, as well as the contemporaneous lavas and dykes associated with the Palæozoic and Mesozoic formations.

The ground-mass may be wholly or partly glass, or cryptocrystalline. Fluxion structure is generally well marked by alternating bands of different texture and colour, or by alternating glassy and spherulitic layers. The vitreous or glassy form is found in *obsidian*, which is a natural volcanic glass in which crystallites or embryonic crystals are frequently developed.

The phenocrysts of rhyolites are orthoclase, including the glassy form sanidine, an acid plagioclase, quartz, biotite, and sometimes augite or hornblende.

Tertiary rhyolites are found in Antrim, in the Lipari group of islands, Nevada, and New Zealand; and recent rhyolites in New Zealand.

INTERMEDIATE GROUP.

Trachytes.—These are in some respects rhyolites without free quartz. The sanidine form of orthoclase is the chief constituent of the ground-mass and also the dominant phenocryst. Hornblende or biotite is nearly always present in true trachytes.

Phonolites.—These rocks are distinguished by the presence of *nepheline* in the ground-mass. Those poor in that alkali-mineral are closely related to the trachytes, and are, by some writers, named *trachytoid phonolites*. The varieties in which nepheline is fairly abundant are sometimes called *nephelinitoid phonolites*.

Andesites.[1]—In most typical andesites the ground-mass is a felted mass of felspar laths, and a residue of glassy matter. The phenocrysts are plagioclase, hornblende, augite, biotite, or hypersthene.

The different varieties of andesite are named from the dominant ferro-magnesian mineral, thus :—

(*a*) *Augite-andesite.*
(*b*) *Hypersthene-andesite.*
(*c*) *Hornblende-andesite.*
(*d*) *Quartz-andesite* or *dacite.*
(*e*) *Mica-andesite.*

Among the accessory minerals, magnetite, ilmenite, apatite, and zircon are usually present.

The andesites that have been altered by thermal waters, steam, or gases are sometimes called *propylite.*

The andesites of United States, New Zealand, and Transylvania are of great importance for their valuable gold- and silver-bearing lodes.

BASIC GROUP.

Basalts.—These occur as lavas, sills, and dykes. The essential minerals are a plagioclase felspar, rich in lime, augite, and olivine. They exhibit every form of texture from the glassy to the holocrystalline.

In the glassy form we have *tachylyte*; and in those basalts in

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[1] So named from the Andes in South America.

which the phenocrysts are embedded in a holocrystalline groundmass we get rocks that are essentially dolerites.

The typical rock of this group is *olivine-basalt.*

SUMMARY.

1. Plutonic rocks occur in boss-like masses that have been uncovered by denudation.

2. They are holocrystalline in structure, and evidently cooled slowly and under great pressure.

3. The order of crystallisation in plutonic rocks is one of *decreasing basicity* ; that is, the basic minerals separate out first, and the acid last.

4. The leading types of the acid plutonics are *Granite* and *Syenite* ; of the intermediate plutonics, *Diorite*, *Gabbro*, and *Norite* ; and of the basic, *Peridotite.*

5. Hypabyssal igneous rocks occur mostly as dykes, and their texture is generally holocrystalline. The acid types are closely related to the granites, and the intermediate to the syenites and diorites. Some of the intermediate families are characteristically porphyritic.

6. The volcanic rocks include all the solid lavas and the dykes that are directly connected with lava streams. They range from the glassy to the holocrystalline forms of texture.

The rhyolites are typical of the acid group, the andesites of the intermediate, and the basalts of the basic.

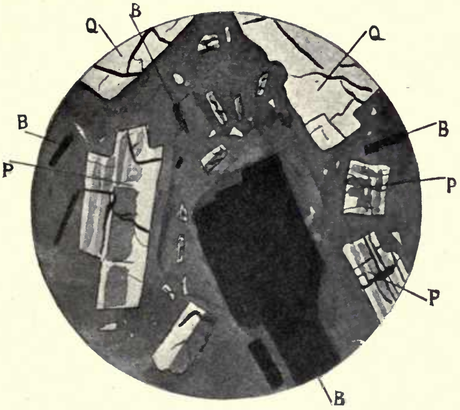

FIG. 145.—Micro-drawing of biotite-dacite from Huanuni.
(After Rumbold.)

Ground-mass, Glass. B, Biotite. P, Plagioclase. Q, Quartz.

FIG. 146.—Microphotograph of olivine-basalt from North Auckland, N.Z., showing phenocryst of plagioclase and ophitic structure of ground-mass; there is a general orientation of felspars.

CHAPTER XVII.

METAMORPHISM AND METAMORPHIC ROCKS.

Metamorphism.

In metamorphic[1] rocks the original constituents of the rocks have in many cases formed new combinations among themselves. The minerals developed by this process of alteration invariably possess a crystalline structure; hence metamorphic rocks are frequently spoken of as *crystalline.* In many metamorphic rocks, the newly developed minerals have arranged or aggregated themselves in more or less parallel layers or *folia* that give rise to the structure called *foliated.* Foliation is characteristic of many metamorphic rocks. Foliated rocks generally split readily into thin plates or flags parallel with the foliation planes. Metamorphic rocks that split in this way are called *schists.*[2]

Genesis of Metamorphism.—The three agencies chiefly concerned in the metamorphism of rock-masses are *heat*, *pressure*, and *water.*

The heat and pressure may arise from three possible sources, namely—igneous intrusions, the intense folding of strata, or the subsidence of crustal blocks within the zone of high subterranean temperatures.

The water may be magmatic, or interstitial in the sedimentary rocks subjected to heat and pressure.

According to the source of the heat, the alteration of rock-masses may be divided into—

(1) *Contact-Metamorphism.*
(2) *Regional-Metamorphism.*

Contact-Metamorphism.—All igneous intrusions produce a certain amount of alteration in the rocks which they invade. In the case of lavas the thermal effects are, as a rule, slight and unimportant. Moreover, the alteration caused by the intrusion of small dykes and thin sills is in most cases remarkably small, and is generally confined to the dehydration and baking of the skin of

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[1] Gr. *meta* = change, and *morphe* = shape.

[2] Gr. *schistos* = easily split.

rock at the actual line of contact. Coals, however, may be changed to anthracite, or even graphite; and pieces of clay entangled in the magma baked into an impure porcelain called *porcellanite.*

Large dykes and plutonic bosses that have cooled slowly and under pressure, frequently effect considerable changes in the rocks into which they intrude. Along the line of contact, the intruded rocks are generally baked and hardened, but as a rule the mere thermal effects of dry heat are among the least conspicuous of the changes effected by the intrusion. In some cases the invaded rock is shattered and impregnated with new minerals for many hundreds or even thousands of yards beyond the actual contact; in other cases it is metamorphosed into a foliated crystalline schist.

The metamorphic effect of great plutonic intrusions is mainly thermal, and hence is greatest at the contact, gradually diminishing as the distance from the intruding mass increases. The amount of change arising from the *contact-action* will depend on the degree of heat, rate of cooling of the igneous mass, the thickness of the superincumbent strata, as well as on the chemical composition and structure of the invaded rocks.

The dominant sedimentary rocks in the rocky crust are sandstones, shales, and limestones. The sandstones are changed into quartzites, the shales into slate or mica-schist, and the limestones into marbles.

Pressure alone will alter argillites and shales into true slates possessing the characteristic *slaty cleavage,* but heat, pressure, and water acting together will usually lead to the development of muscovite mica on a grand scale. In the zone of greatest pressure, the shale may be changed completely into mica, forming a phyllite; or in cases where the shale is sandy, into a mica-schist.

Where a boss of granite has intruded slates there is frequently developed in the slate a crop of what are called *contact minerals.* These secondary crystalline minerals are mostly simple silicates of alumina, and the commonest are *chiastolite* and *staurolite.* When the intruded rock contains sufficient lime and alkali to combine with the free silica many complete silicates may be developed, conspicuously *muscovite* and *actinolite.*

Pure limestones are changed to granular marbles, while impure limestones give rise to a series of complex lime-silicates, of which *grossularite* (lime-garnet), *actinolite,* and *diopside* (lime-pyroxene) are the most frequent.

The mere fact that a series of sedimentary rocks becomes more and more altered as a granitic boss is approached does not, of itself, afford conclusive proof that the granite is intrusive in the sedimentary formation. Many granitic massifs are fixed blocks of great antiquity, against which younger formations have sometimes been crushed and intensely folded, and in the process have suffered a high degree of metamorphism. Hence when an altered sedimentary formation lies against a granite boss, it is not safe, in the absence of *apophyses*[1] or intrusive veins on the fringe of the igneous mass, to conclude that the granite is younger than the altered clastic rocks with which it is in contact.

The slower the magma cools, the greater are the changes effected by it. Hence we usually find that the greatest alteration has been effected by granites, diorites, and other plutonic masses of coarse texture.

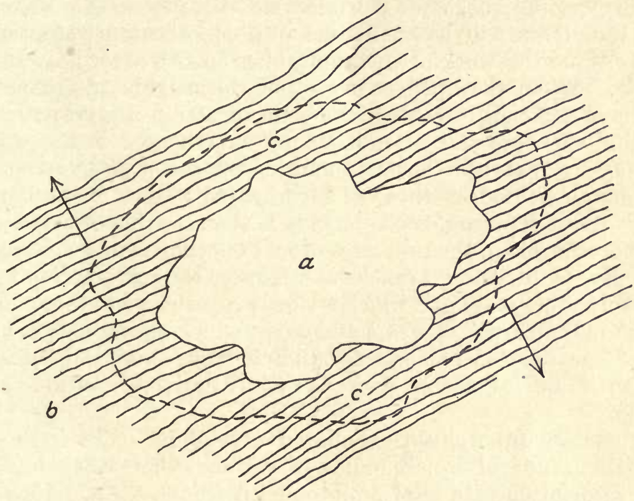

FIG. 147.—Showing aureole or zone of metamorphism, N.S.W.
(*a*) Granite boss. (*b*) Mica-schist. (*c*) Zone of tin impregnation.

Among the non-metallic minerals introduced into or developed in the country-rock by the igneous intrusion are biotite, tourmaline, hornblende, epidote, felspars, garnets, and idocrase; and of metallic minerals, ores of tin, wolfram, copper, gold, silver, and iron. The impregnation of the country-rock within the aureole or zone of metamorphism with tin and wolfram is a characteristic feature of granite intrusions.

Obviously such extensive alteration and impregnation must be due to some other agency than mere dry heat.

Daubree's experiments on silicates and rocks have shown that not dry heat alone, nor even vapours or gases, would be sufficient to effect changes of any moment; but that superheated water,

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[1] Gr. *apophusis* = an offshoot.

under great pressure, was the most important agent concerned in metamorphism. To prove this he partially filled a glass-tube with water, sealed both ends, and placed it in a strong iron tube which was closed, and exposed to a temperature below red heat for several days. The glass-tube was attacked by the water and converted into a zeolitic mineral. In some places a laminated, in others a spherulitic, structure was present. With superheated steam he obtained orthoclase and a micaceous mineral.

During the process of cooling, the intrusive magma will probably liberate enormous quantities of steam, which will penetrate the surrounding rocks for considerable distances. At a certain point the steam will be condensed into superheated water, which will continue the work of metamorphism in the outer zone of the aureole. When the igneous mass and the neighbouring country-rock have sufficiently cooled, the zone of steam and vapour surrounding the boss will be invaded by superheated water, and in this way we may get the metamorphic effects of the vapour and gases supplemented by those of superheated water.

The intrusion of an igneous magma is thus capable of performing an important rôle in the processes of metamorphism and mineralisation. By its intrusion it cracks and fissures the surrounding rocks. It is a source of great heat, which is slowly transferred to the country-rock; and is a carrier of steam and gases, which are capable of altering the constitution of the surrounding rocks, and impregnating them with mineral matter, perhaps mainly derived from the parent magma.

Regional-Metamorphism.—Foliated crystalline rocks frequently cover thousands of square miles in regions where they have no direct association with known plutonic intrusions. And, singularly enough, these rocks for thousands of square miles, and sometimes throughout an enormous thickness, may exhibit as high a degree of metamorphism as the most intense alteration produced on the borders of a great plutonic boss.

The origin of this widespread regional-metamorphism is not well understood. By some it is believed to have been caused by the uprising of enormous floods of plutonic magmas that consolidated at a considerable depth and have never been uncovered by denudation. In other words, this view supposes that regional-metamorphism is merely an exaggerated kind of contact-metamorphism.

Another hypothesis postulates that great crustal blocks lying under piles of younger strata have been depressed by subsidence until brought within the influence of a high subterranean temperature. This view is merely a modification of the Huttonian plutonic theory, according to which blocks of rock were depressed until they reached a zone where they were first softened and melted, eventually crystallising as they cooled.

The temperature of the Earth increases with increasing depth below the surface, but is not proportional to the depth. In volcanic regions the zone of high temperature lies close to the surface, but in non-volcanic regions the temperature-gradient varies enormously. In some regions the rate of increase of temperature is as high as 1° Fahr. for every 60 feet of depth; in other places it is not more than 1° Fahr. in 200 or more feet. Moreover, the rate of increase of temperature is not uniform. But it is not unreasonable to suppose that with considerable subsidence and a thick covering of strata a sufficient heat might be encountered at a depth of a few miles to effect in the presence of superheated water great alterations in the constitution of rock-masses, without actual softening and fusion, as required by the Huttonian theory.

The intensity of metamorphism of rocks is in many cases, perhaps the majority, proportional to the amount of crushing, folding, and plication they have suffered. The metamorphism induced by intense folding and other crustal movements constitutes what is sometimes called *dynamo-metamorphism*. In this case we are warranted in assuming that the heat and pressure of crustal movement in conjunction with water were important, but not necessarily the sole, agents of metamorphism. For it is obvious that the powerful lateral or tangential stresses generated by crustal movement, can only become effective in the production of intense folding and plication when they are strongly resisted by the vertical stress of a pile of superincumbent strata. The existence of such a pile of strata would necessarily imply considerable subsidence, sufficient perhaps to bring the basement rocks within the influence of a high subterranean temperature, not sufficiently high to cause fusion, but enough to supplement the heat generated by the folding.

But intensely folded strata are not always altered into metamorphic rocks. On the contrary, they frequently exhibit little or no evidence of internal change. And crystalline schists are not always folded. The highly altered mica-schists of Central Otago in New Zealand lie perfectly horizontal, or are gently undulating, over thousands of square miles, and they are not connected with any visible plutonic masses.

The genesis of regional-metamorphism is a difficult problem for which no satisfactory solution has been formulated. When we review the available evidence, it does not seem unwarrantable to assume that regional-metamorphism may be caused partly by folding and partly by the subsidence of crustal blocks till they come within the zone of considerable subterranean heat.

Metamorphic Rocks.

Metamorphic rocks may be *schistose* or *massive.* In the schistose group, the original matter has become for the most part crystalline, and a *foliated* or schistose structure has been induced by the arrangement of the newly-formed crystalline constituents in short leaves or *folia* [1] lying more or less parallel with one another.

The separate folia may consist of one or several minerals. They usually occur as flat lenses, sometimes even and parallel, but most frequently overlapping, uneven, and undulating, puckered, or plicated. In many of the more highly altered rocks they thin out rapidly in all directions, again increase in size, and once more thin out, and so on indefinitely.

The folia may vary from a fraction of an inch to several inches or even many feet thick. Fossils present in the original sediments are usually completely obliterated by the development of the crystalline structure.

The foliation planes may be parallel to the original bedding planes or they may follow any direction. The foliation is doubtless developed in the rock when under the influence of enormous pressure; and it is not improbable that the foliation planes, like slaty-cleavage to which they are closely related, always lie at right angles to the direction of the stress.

Rocks are found showing all degrees of metamorphism from highly contorted granitoid gneissic schists to altered sediments in which the character of the original sediments can still be traced.

Many of the older schists are believed to be altered igneous rocks of great antiquity. The greenstones (altered andesites and basalts) forming the hanging-wall of the Alaska-Treadwell ore-body on Douglas Island, Alaska, possess a well-developed schistose structure, as also do some of the greenstones or amphibolites associated with the gold-bearing lode-formations at Kalgoorlie.

Among the massive metamorphic rocks that possess a crystalline structure, but are not foliated, are marble and quartzite.

Foliated Schists.

The leading and most prevalent types of these rocks are as follow:—

Gneiss is a schistose aggregate of quartz, felspar, and mica (muscovite or biotite). Accessory minerals: usually hornblende, magnetite, garnet, rutile, tourmaline, and pyrite. Abundant in Canada, Highlands of Scotland, Scandinavia, and New Zealand. Usually a rock of

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[1] Lat. *folia* = leaves.

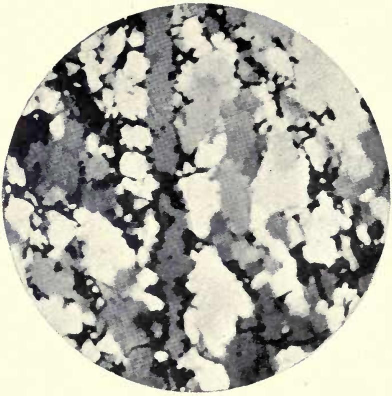

FIG. 148.—Photomicrograph of quartz-biotite-schist from Central Otago, N.Z.

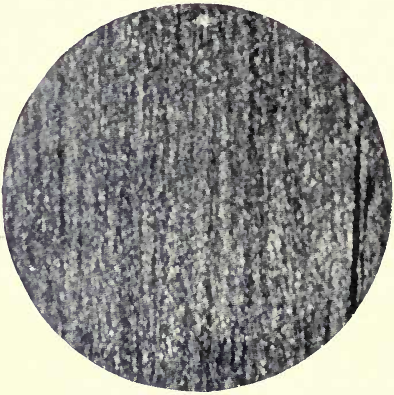

FIG. 149.—Microphotograph of phyllite from Central Otago, N.Z.

great antiquity. It may graduate into mica-schist on the one hand, or become granitoid on the other.

The different varieties of gneiss are named after the dominant ferro-magnesian mineral.

Mica-Schist consists of alternating folia of mica (mostly muscovite) and quartz. Accessory minerals: magnetite, garnet, rutile, and pyrite. Abundant in Canada, Highlands of Scotland, Scandinavia, Alps, New South Wales, Western Australia, and New Zealand.

Chlorite-Schist is a schistose aggregate of scaly chlorite, usually with quartz. Accessory minerals: magnetite, specular iron, felspar, talc, mica, actinolite, and apatite. Commonly occurs as subordinate bands in mica-schist. In many cases appears to be a metamorphosed basic igneous rock. The characteristic colour is a pale olive green.

Hornblende-Schist is generally an aggregate of hornblende, quartz, felspar, and mica. Accessory minerals: magnetite, garnet, and epidote. This schist is probably an altered igneous rock. It commonly occurs in association with gneiss and mica-schist.

Actinolite-Schist, composed mainly of light- or dark-green actinolite, often in clustering or radiating sheaves, is a common associate of mica-schist and gneiss.

Quartz-Schist is a flaggy quartzite that breaks readily into thin laminæ. Sometimes the splitting is facilitated by the presence of mica along the foliation planes. In this case we get a *micaceous quartz-schist*, which may graduate into an ordinary mica-schist. The common accessory minerals are actinolite, garnet, specular iron, and magnetite. Quartz-schist forms bands associated with mica-schist and slate in the older Palæozoic formations. Found in all the continents.

Talc-Schist consists of scaly talc, often with some quartz, chlorite, or mica. Colour pale-green or greenish-grey. Feels greasy and is quite soft. Accessory minerals: magnetite, tourmaline, felspar, magnesite, and actinolite. Frequently associated with mica-schist as small subordinate bands.

Phyllite, a highly altered clay-shale in which an abundance of mica has been developed. When the mica forms the dominant constituent, the rock possesses a silvery-grey colour and a silky lustre. Quartz is frequently present. Phyllite is intermediate between an ordinary clay-slate and mica-schist, into either of which it may pass insensibly.

Clay-Slate is a compact finely-granular clay-rock. Splits readily into thin plates in a direction parallel with the slaty-cleavage, which may coincide with the original planes of deposition, or lie in any other direction. The colour ranges from grey to green, blue, and purple. Clay-slate is essentially composed of hydrous silicate of alumina and various other silicates. The accessory minerals are quartz, mica, felspar, rutile, iron oxides, and pyrite. *Graphite-slate* contains a large amount of graphite. *Spotted-slate* is a slate containing little knots or spots which would appear in some cases to be incipient forms of *chiastolite* or *andalusite.* These minerals are frequently developed in slates near igneous contacts, and when relatively abundant give rise to the varieties of slate called *chiastolite-slate* or *andalusite-slate.*

As a rule, the schistose structure is best developed in fine-grained rocks, but under the influence of great pressure even conglomerates may become schistose.

Massive Crystalline Rocks.

Marble is a granular crystalline aggregate of calcite of fairly uniform texture. The accessory minerals may be mica (generally muscovite), talc (or more rarely graphite scales), garnet, actinolite, tremolite, or molybdenite scales. A marble is merely a metamorphosed limestone ; and when the original limestone was pure we get a high-class marble, and when impure a low-grade marble, the impurities being changed into the accessory minerals.

Quartzite is a rock consisting essentially of quartz grains cemented with silica. It is an altered sandstone and possesses a crystalline texture induced by heat in the presence of water. The grains frequently present a semi-fused appearance. Quartzite can be formed from blocks of sandstone subjected to prolonged heat. The metamorphism is probably accelerated by the presence of superheated water. Where igneous rocks have intruded into sandstones, a zone of the latter surrounding the intrusive mass is frequently altered into typical quartzite.

SUMMARY.

(1) Metamorphic rocks generally possess a crystalline structure. They may be foliated or massive. In the foliated rocks, the crystalline mineral constituents are arranged in more or less parallel

or overlapping lenses. The foliated rocks split readily along the foliation-planes; and are therefore called schistose.

(2) The massive metamorphic rocks are marble and quartzite.

(3) The most abundant crystalline schists are gneiss, mica-schist, chlorite-schist, quartz-schist, talc-schist, and phyllite.

(4) The alteration or metamorphism of rocks is mainly due to heat, pressure, and superheated water.

(5) The metamorphism may be what is called *contact-metamorphism*, which is caused by igneous intrusions and hence quite local; or *regional-metamorphism*, which affects large areas of rock.

(6) The effects of contact-metamorphism have been successfully imitated by Daubree and others on artificial compounds.

(7) The origin of regional-metamorphism is still obscure. It may be due (*a*) to the uprising of floods of plutonic magmas that have consolidated at a considerable depth and have never been exposed by denudation; (*b*) to the subsidence of large crustal blocks to the zone of subterranean heat; or (*c*) to the intense folding and plication of rocks subjected to the load of a pile of superincumbent strata.

It is not improbable that in certain situations, one, two, or all of these together, may have been concerned in the process of metamorphism.

CHAPTER XVIII.

FOSSILS: THEIR OCCURRENCE, PRESERVATION, CLASSIFICATION, AND USES.

The remains of animals and plants that have been embedded in rocks, as well as all traces, casts, impressions, and trails of what were at one time living organisms, are called fossils.

Fossils are found in the majority of stratified rocks; and since most stratified rocks are of marine origin, it is not surprising to find that the majority of fossils belong to organisms that lived in the sea.

The most abundant fossils are the shells of marine molluscs; and after these come corals and foraminifera.

Preservation of Fossils.—Let us consider the case of the molluscs. Most molluscs are provided with a calcareous shell or covering. When the animal dies and the soft parts decay, the shell usually becomes filled up with sand or mud, and is eventually buried in the sediments that are continually accumulating on the sea-floor.

Shells buried in a mud or fine sediment that subsequently becomes hardened into an impervious rock are usually perfectly preserved, with the exception perhaps of the original colouring. But shells embedded in a sandstone through which water can percolate freely are frequently dissolved and removed by the water, and there remain only *external casts*, or impressions of the *exterior* of the shells. In cases where the shell was filled with sediment at the time it was buried, besides the external mould, there will be found, when the shell is dissolved, an *internal cast* reproducing the exact shape of the *interior* of the shell.

By filling with plaster the space from which the shell was dissolved a *hollow cast* is obtained that is in all respects a replica of the original shell. If, on the other hand, we remove the internal cast, and fill the whole interior of the mould or impression from which it was removed with plaster, we shall get a solid representation of the outward form of the shell before its burial.

When a shell is gradually replaced by mineral matter deposited from water percolating through the rock, we frequently get a complete reproduction of the whole organism even to the minutest

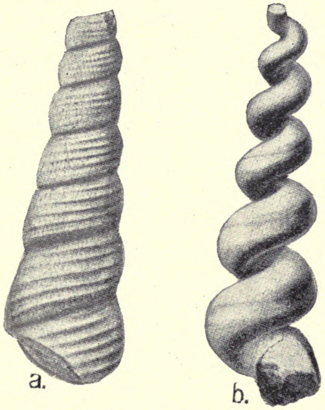

FIG. 150.—Showing fossil casts of *Turritella*.
(*a*) Cast of exterior of shell. (*b*) Cast of interior.

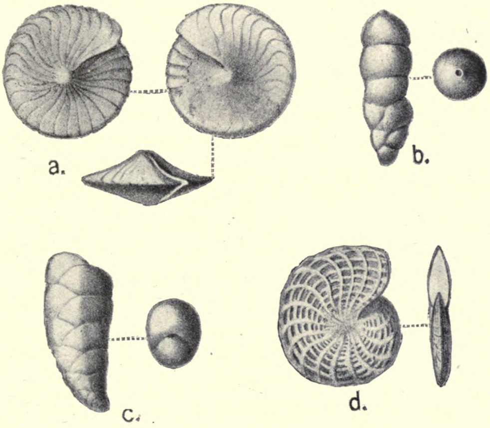

FIG. 151.—Showing fossil foraminifera.
(*a*) *Amphistegina*. (*b*) *Clavulina*. (*c*) *Textilaria*. (*d*) *Polystomella*.

detail. The carbonate of lime of the shell may be replaced by carbonate of iron, pyrite, or silica. Siliceous replacements of bones and wood are quite common, and often they preserve the internal structure with marvellous exactness.

Shells which live in sand or mud become buried, as a rule, in the place where they lived. But many shells are cast up on the beach, where they are broken up into sand by the pounding action of the waves. It is in this way that shelly sands are formed. Thick shells that are not easily comminuted soon become rounded and water-worn.

The fossil-shells that occur in rocks composed of littoral deposits are frequently fragmentary and water-worn.

Deltaic and estuarine deposits may contain the remains of land animals and plants, mingled with estuarine and marine forms.

Shelly limestones are usually composed of the dead shells of gregarious molluscs that grew on shell-banks; and coral-limestones are formed where the coral-builders lived; but deep-sea shells are not infrequently found in shallow-water deposits, and littoral shells in deep-sea sediments where they have been carried by sea-currents.

The remains of land animals and plants are sometimes carried far out to sea, where they become buried among marine organisms; but marine deposits are typically distinguished by the presence of marine organisms, and terrestrial deposits by terrestrial organisms.

Fossiliferous Rocks.—As a rule the best-preserved fossils are found in rocks composed of fine sediments. Clays, marls, shales, and limestones frequently contain a rich and varied assemblage of fossils in a beautiful state of preservation.

The best leaf-impressions are met with in fissile shales and argillaceous sandstones, and they are most numerous where the rock is black and carbonaceous.

Coarse sandstones, grits, and conglomerates are characteristically poor in organic remains; and when shells are present in them, they are usually broken and water-worn. In most sandstones the fossils are represented by *internal casts*, and impressions of the exterior of the shells or organisms.

Volcanic tuffs intercalated with marine strata are sometimes richly fossiliferous, but igneous rocks are devoid of all organic remains except those that occur in blocks derived from fossiliferous sedimentaries in the neighbourhood of the volcanic vent.

Derived Fossils are comparatively common in the pebbles and boulders of pebbly beds and conglomerates. Conglomerates, like all other sedimentary rocks, are composed of material derived from older rock-formations, many of which were fossiliferous. When a fossiliferous rock-formation becomes broken up by denudation some of the pebbles may contain fossils, and in this way the conglomerate, of which these pebbles eventually become a constituent, may contain *derived fossils*. A Tertiary conglomerate may contain Tertiary shells embedded in the sandy matrix, and derived fossils of Silurian age embedded in the pebbles. The fossils met with in the matrix are contemporaneous, and belong to molluscs that lived in the sea at the time the pebbles and sands were deposited. But this requires some qualification. Derived fossils do not always occur embedded in pebbles or blocks. They are sometimes met with in sandy and clayey rocks mingled with the contemporaneous shells from which they cannot always be easily distinguished. In places where the sea-coast is fringed with low-sloping cliffs composed of fossiliferous sands, clays, marls, or shales, it sometimes happens that well-preserved shells become liberated by the crumbling away of the rock and fall on to the beach, where they become embedded in the sands or mud accumulating on the sea-floor.

Classification of Living Organisms.

All living organisms are divided into two kingdoms, namely :—

I. Animal kingdom.
II. Vegetable kingdom.

THE ANIMAL KINGDOM.

The study of the animals that now inhabit the globe belongs to the domain of the science known as *Zoology*. The branch of Zoology which concerns itself with fossil organisms is called *Palæontology*.[1]

For convenience of study, animal life has been subdivided into *Species*, *Genera*, *Families*, *Orders*, *Classes*, and *Sub-kingdoms*, in much the same way as the human race is divided into *Individuals*, *Families*, *Tribes*, *Nations*, and *Races*. Thus the related members of a household constitute a Family, a number of families form a *Tribe* or Clan, a number of tribes form a Nation, and several related nations constitute a Race.

The individuals of any kind of animal are called *species* ; and a *species* may be defined as comprising those individuals that are the same in all essential features, and reproduce their kind true to the type.

A *genus* includes all the *species* that are nearly related by some prominent structural characteristic. Thus all the species of the cat-kind, whether domestic or wild, are included in the genus *Felis*. In this way we have :—

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[1] Gr. *palaios* = ancient, *onta* = beings, and *logos* = a description or discourse.

Felis catus = the domestic cat.
Felis tigris = the tiger.
Felis leo = the lion.

Similarly all the members or species of the dog-kind are grouped in the genus *Canis*. Thus we have :—

Canis familiaris = the domestic dog;
Canis lupus = the wolf;
Canis vulpes = the fox.

Related genera are grouped in *Families*, related families in *Orders*, related orders in *Classes*, and related classes in *Sub-kingdoms*, of which there are nine.

The groups of animals which are known to occur in the fossil state, beginning with the simplest forms and ending with the most highly organised, are as shown in the following table :—

OUTLINE CLASSIFICATION OF ANIMAL KINGDOM.

Sub-kingdoms.	Classes.	Fossil Types.
I. Protozoa .	Rhizopoda.	Foraminifera, Radiolaria.
II. Porifera .	Spongiæ.	Sponges.
III. Cœlenterata	(*a*) Hydrozoa.	Graptolites.
	(*b*) Actinozoa.	Coral-reef builders.
IV. Echinodermata	(*a*) Crinoidea.	Sea-lilies.
	(*b*) Asteroidea.	Starfish.
	(*c*) Echinoidea.	Sea-urchins.
	(*d*) Blastoidea.	
	(*e*) Cystoidea.	
V. Annulata .	Annelida.	Worms.
VI. Molluscoidea .	(*a*) Polyzoa.	Sea-mats.
	(*b*) Brachiopoda.	Lamp-shells.
VII. Mollusca .	(*a*) Lamellibranchiata.	Oysters and common bivalves.
	(*b*) Gasteropoda.	Univalve shells.
	(*c*) Cephalopoda.	Nautilus, ammonites.
VIII. Arthropoda .	(*a*) Crustacea.	Crabs.
	(*b*) Arachnoidea.	Spiders, scorpions.
	(*c*) Insecta.	Insects.
IX. Vertebrata .	(*a*) Pisces.	Fishes.
	(*b*) Amphibia.	Frogs.
	(*c*) Reptilia.	Reptiles.
	(*d*) Aves.	Birds.
	(*e*) Mammalia.	Mammoth, seal, whales.

Protozoa.[1]—This is the lowest division of the animal kingdom. The organisms of this group consist of a single cell of jelly-like matter; and some protect themselves with a strong covering secreted from the sea-water.

Only those possessing a hard cover are preserved as fossils. Among these we have the *Foraminifera*,[2] which secrete a carbonate of lime covering, and the *Radiolaria*,[3] which form a hard case of silica.

The shells of the *Foraminifera* are shaped like flasks or flattened globes with a biconvex section, or like globes and flasks entwined.

The walls of the shells are pierced with numerous holes through which the animal extends thread-like organs. The *Foraminifera* form important deposits on the floor of the deep seas; and they have played an important part as limestone builders in the earlier periods of the Earth's history, and as chalk builders in the Cretaceous.

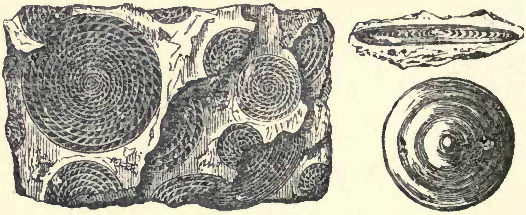

Fig. 152.—Nummulites, Lower Tertiary Species.

Among the best-known genera of *Foraminifera* are *Dentalina*, *Nodosaria*, *Cristellaria*, *Globigerina*, *Rotalia* and *Nummulites*.

The *Radiolaria* secrete siliceous skeletons that are often a geometrical framework of extreme beauty. They form deposits of ooze on the floor of the deep sea; and as fossils are found in cherts and other siliceous rocks.

Porifera.—This sub-kingdom includes the sponges, which are somewhat more complex organisms than the protozoans. The body is generally supported on a framework or skeleton of horny or siliceous fibres, or of spicules which may be composed of silica or carbonate of lime.

The majority of the sponges are marine. The portions found fossil are generally the siliceous spicules and fibres.

Cœlenterata.—This group contains the Hydrozoans and Actino-

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[1] Gr. *protos* = first, and *zoon* = an animal.

[2] Lat. *foramina* = holes, and *fero* = I bear.

[3] Lat. *radius* = a ray.

zoans, which are of immense geological importance. The *Hydrozoans* [1] include the *graptolites*,[2] which have long been extinct, but are of great value as a means of determining the age of the rocks in which they occur. Graptolites are found in shales, slates, and argillaceous sandstones, in which they occur as flattened bodies that are usually converted into graphite.

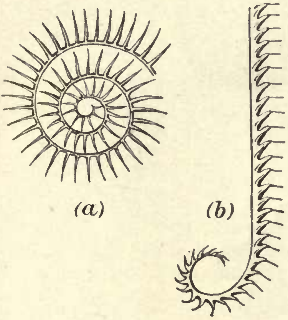

FIG. 153.—(a) *Monograptus spiralis.*
(b) *M. cyphus.*

FIG. 154.—*Diplograptus.*

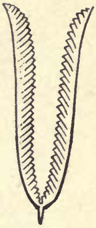

FIG. 155.—*Didymograptus.*

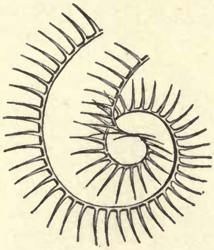

FIG. 156.—*Rastrites.*

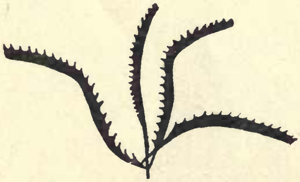

FIG. 157.—*Tetragraptus.*

The *Actinozoans* include the well-known coral-builders; they consist of a soft body supported in a cup of carbonate of lime. They build up huge coral reefs and enormous masses of limestone. They are perhaps the most important of all living organisms considered as geological agents.

Echinodermata.[3]—These are, as the name implies, spiny-skinned animals. They possess a calcareous covering made up of a number of plates. The portions found fossil are the spines and

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[1] Gr. *hudor*=water, and *zoon*=an animal.
[2] Gr. *graphein*=to write, and *lithos*=a stone.
[3] Gr. *echinos*=a hedgehog, and *derma*=skin.

plates. The *Crinoidea*, *Echinoidea*, and *Asteroidea* are the chief classes of this sub-kingdom.

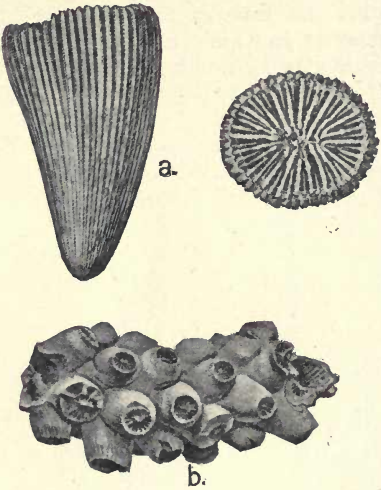

FIG. 158.—Showing corals.
(*a*) *Oculina*. (*b*) *Trochocyathus*.

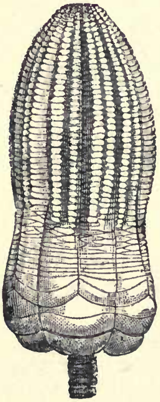

FIG. 159.—Fossil sea-lily, *Encrinus*.

FIG. 160.—Fossil sea-lily, *Pentacrinus*.

The *Crinoidea*,[1] called crinoids or sea-lilies, usually consist of long flexible stalks with a calyx at the upper end. The calyx contains the internal organs of the animal, and is protected with plates symmetrically arranged. Round the calyx there is a number of flexible arms which, like the stalk, are encased in calcareous plates. The animal is attached to objects on the sea-floor by the stalk, which is jointed and flexible. Broken arms and stalks of crinoids are sometimes so plentiful as to compose masses of limestone.

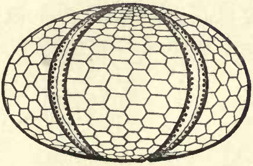

Fig. 161.—Fossil sea-urchin, *Palæchinus.*

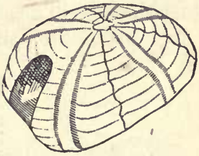

Fig. 162.—Fossil sea-urchin, *Nucleolites.*

The *Echinoidea*[2] include the well-known Sea-urchins so often cast up on sandy beaches or seen in rocky pools below high-water mark. They are usually globular or heart-shaped animals enclosed in a spiny case or shell composed of closely-fitting calcareous plates. The spines, plates, and frequently whole shells, are found fossil.

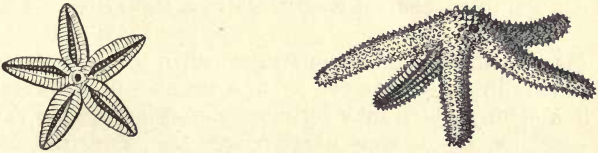

Fig. 163.—The fossil starfish, *Palæaster,* from the Cambrian.

The *Asteroidea*[3] or Starfishes consist of a central flattened disc with several radiating arms.

The *Ophiuroidea*[4] are related to the Starfishes. They comprise a remarkable group of *Brittle-stars* in which the viscera are excluded from the arms. They consist of a central flattened disc-like body from which project five long flexible arms used by the animal as a means of locomotion.

[1] Gr. *krinon* = a lily, and Lat. *oides* = like.

[2] Gr. *echinos* = a hedgehog, and Lat. *oides* = like.

[3] Gr. *aster* = a star, and Lat. *oides* = like.

[4] Gr. *ophis* = a snake, and Lat. *oides* = like.

Annulata.[1]—The *annelids* or segmented worms are the only ones found fossil. Some of the annelids secrete calcareous tubes which have been preserved in shales and slates. The former existence of worms is also known by the fossil trails left in muds now hardened into shales, and by the worm-burrows made in sands now converted into sandstones.

Worm-burrows and trails are among the oldest known fossils. Many of the so-called fucoids which are found in rocks of all ages, but are particularly abundant in the Cretaceous, are probably the remains of tube-building Terebelloid annelids.[2]

Molluscoidea.[3]—These comprise the *Polyzoa* [4] and *Brachiopoda*,[5] which are soft-bodied animals provided with a calcareous shell or covering.

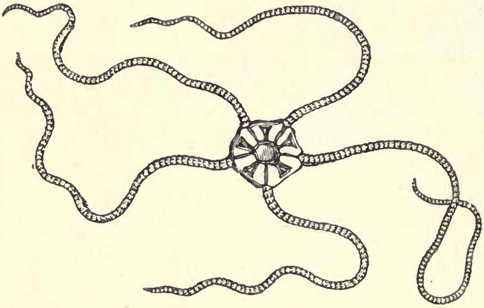

FIG. 164.—Showing fossil brittle-star, *Ophioderma.*

The *Polyzoa* or Sea-mats, sometimes called *Bryozoans*, are tiny animals living in a separate cell; but a number of individuals are united in a colony which may form an encrusting mat on the rocks on the seashore, or on some other organism. They are found as fossils in rocks of all geological ages.

The *Brachiopoda* comprise one of the most important classes of fossil shells. They are poorly represented by living species, but occur in great abundance in the Palæozoic and Mesozoic formations.

Brachiopods are soft animals enclosed in symmetrical bivalve shells, the valves of which are typically unequal in size. The larger valve is called the *ventral* valve, and the smaller, the *dorsal*. In most genera, the valves are locked together at the hinge. The ventral valve is usually perforated with a hole called the *foramen*,

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[1] Lat. *annulus* = a little ring.

[2] F. A. Bather, *The Geological Magazine*, Dec. 1911, p. 549.

[3] Lat. *mollis* = soft, and Lat. *oides* = like.

[4] Gr. *polus* = many, and *zoon* = an animal.

[5] Gr. *brachion* = an arm, and *pous, podos* = a foot.

for the passage of a ligament by which the animal attaches itself to solid objects.

Most brachiopod shells contain an internal calcareous loop or spiral for the support of the breathing organs.

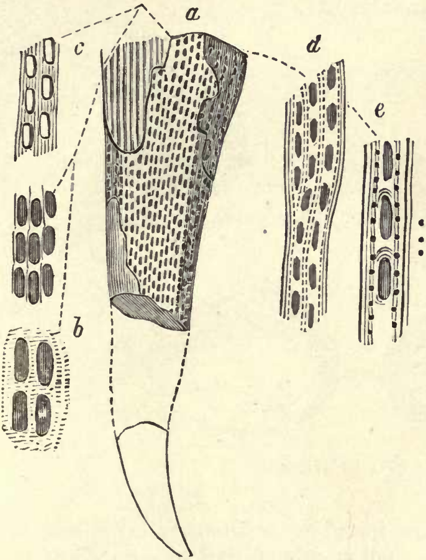

Fig. 165.—Showing fossil polyzoan, *Fenestella.*

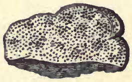

Fig. 166.—Showing fossil polyzoan, *Monticulipora.*

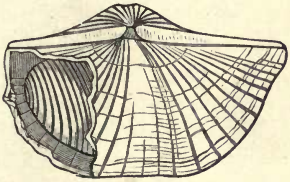

Fig. 167.—Fossil brachiopod, *Spirifer,* showing internal spiral loop.

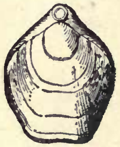

Fig. 168.—Fossil brachiopod, *Terebratula* (lamp-shell), showing foramen.

Mollusca.—This sub-kingdom is of immense importance. It is represented by thousands of living and extinct species. All the land shells, and practically all the marine shells, so numerous in the shallow seas, are molluscs.

Nearly all molluscs possess a hard calcareous shell, and all have an elaborate nervous system and a heart. The three great divisions of the mollusca are :—

(1) Lamellibranchiata.
(2) Gasteropoda.
(3) Cephalopoda.

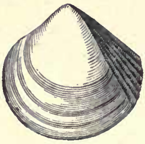

Fig. 169.—*Protocardium.*

Fig. 170.—*Inoceramus.*

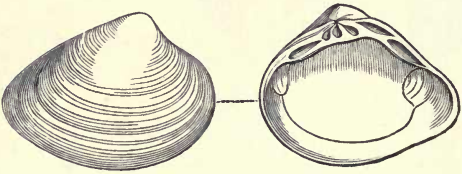

Fig. 171.—*Cyrena.*

The *Lamellibranchiata* [1] are found in freshwater lakes and the sea. They possess a bivalve shell which consists of a right and left valve. Among familiar shells of this class we have the *mussel*, *cockle*, and *oyster*.

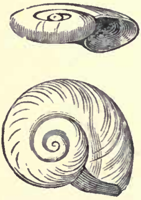

Fig. 172.—*Planorbis.*

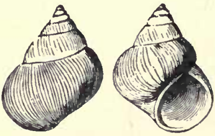

Fig. 173.—*Paludina.*

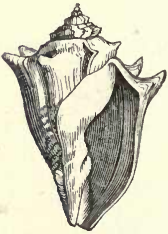

Fig. 174.—*Voluta.*

The *Gasteropoda* [2] are molluscs with only one shell or valve, and hence are spoken of as *univalve*. The shell may be basin-shaped, as in *Patella*; or coiled in a flat or a turreted spiral. Some

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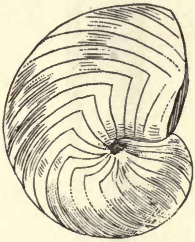
[1] Lat. *lamella* = a little plate, and *branchiæ* = gills.

[2] Gr. *gaster* = a belly, and *pous, podos* = a foot.

gasteropods live on the land, some in fresh water, and a great many in the sea. All possess a distinct head with eyes and ears.

The *Cephalopoda* [1] are the most highly organised of the mollusca. They include the *Nautilus*,[2] the *Octopus* or *Cuttle-fish*, the *Squid*, and two important orders that are now extinct, the *Ammonites* [3] and *Belemnites*.[4] The *Nautilus* possesses a beautiful chambered shell.

The *Ammonites* have shells resembling those of the Nautilus, but more highly ornamented. The *Belemnites* appear to have resembled the modern squids. Both the Ammonites and Belemnites became extinct about the close of the Mesozoic period.



175.—*Nautilus.*

Fig. 176.—*Goniatites.*

Fig. 177.—*Ceratites.*

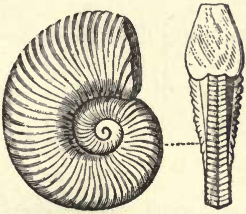


Fig. 178.—*Ammonites.*

Fig. 179.—*Scaphites.*

Arthropoda.[5]—These are animals with jointed limbs and bodies divided into segments. They are divided into (1) the *Crustacea*, (2) *Arachnoidea*, and (3) *Insecta*.

The *Crustacea* include the crabs, lobsters, cray-fish, shrimps, and an important extinct group called *Trilobites* that are typically

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[1] Gr. *kephale* = a head, and *pous*, *podos* = a foot.

[2] Gr. *nautilus* = a sailor.

[3] So named after Jupiter Ammon.

[4] Gr. *belemnon* = a dart.

[5] Gr. *arthron* = a joint, and *pous* = a foot.

characteristic of the older Palæozoic formations. The Trilobites[1] owe their name to the three-lobed arrangement of the body segments, the central lobe of segments being flanked by two other lobes, one on each side.

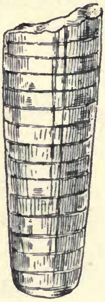

Fig. 180.—*Orthoceras.*

Fig. 181.—Guard of *Belemnites*, showing chambered phragmocone in top of cavity.

Fig. 182.—*Belemnitella.*

The Trilobites are the most distinctive of the older Palæozoic fossils, and are of great value as a means of determining the age of the rocks in which they occur.

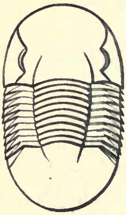

Fig. 183.—*Illænus.*

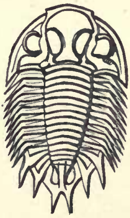

Fig. 184.—*Lichas.*

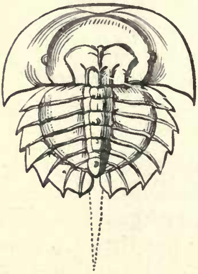

Fig. 185.—*Prestwichia.*

The *Merostomata*,[2] which are represented at the present day by

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[1] Gr. *treis* = three, and *lobos* = a lobe.

[2] Gr. *meros* = a thigh, and *stoma* = a mouth.

the King-crabs, also occur in the older formations, a well-known form being the *Pterygotus*.

The *Decapods* [1] include the crabs and lobsters.

The *Entomostraca* [2] are minute crustaceans, many of which have the entire body enclosed in a shell composed of two valves united along the back by a hinge which permits the shell to be opened and shut at will. The best known of this class are the *Water-fleas*, which are common in the oldest rocks, and are still represented by many living species.

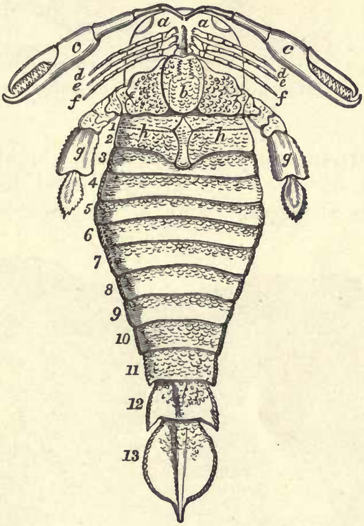

Fig. 186.—*Pterygotus*. (Restored by H. Woodward.)

Vertebrata.—These are subdivided into five great classes :—

(1) *Pisces* = Fishes.
(2) *Amphibia* = Frogs.
(3) *Reptilia* = Reptiles.
(4) *Aves* = Birds.
(5) *Mammalia* = Mammals.

The *Pisces* or fishes are the oldest known vertebrates. The two orders of fishes recognised in a fossil state are the *Ganoidei* [3] and *Teleostei*.[4]

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[1] Gr. *deka* = ten, and *pous*, *podos* = a foot.

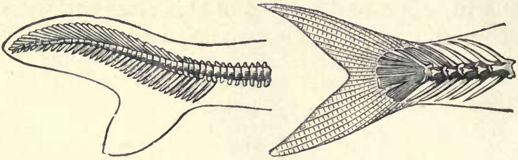
[2] Gr. *entomon* = an insect, and *ostrakon* = a shell.

[3] Gr. *ganos* = brightness, and Lat. *oides* = like.

[4] Gr. *teleos* = complete, and *osteon* = a bone.

Among typical ganoids are the *shark* and *sturgeon*, both characterised by the possession of *heterocercal*[1] tails. The former are marine, the latter freshwater fishes.

The ganoids first appear in the Silurian, and from the Devonian to the close of the Mesozoic they predominate among fossil-fish.



Heterocercal. Homocercal.

FIG. 187.—Fish-tails.

The *Teleostei* are in many respects a more highly organised order than the ganoids, of which they are the lineal descendants. They first appear in the Cretaceous and include most existing fishes.

FIG. 188.—Showing the fossil salamander-like amphibian *Branchiosaurus salamandroides* (Fritsch), twice natural size.

The *Teleostei* are characterised by the presence of *homocercal*[2] tails. They are typically represented by the trout, perch, herring, cod, mullet, and sole.

The *Amphibia*,[3] sometimes called Batrachians, are animals which begin life as water-breathers, like fishes, and later become air-

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[1] Gr. *heteros*=other, and *kerkos*=a tail.

[2] Gr. *homos*=the same or whole, and *kerkos*=a tail.

[3] Gr. *amphi*=both, and *bios*=life.

breathers. They form a connecting-link between the fishes and reptiles.

The amphibians are represented by the ancient and extinct order of *Labyrinthodonts*,[1] which possessed crocodile-like bodies; and by the frogs, toads, and newts.

The *Reptilia* first appeared in the Carboniferous, but it was not till the Trias that they became numerous. They reached their fullest development in the Jurassic and Cretaceous epochs. The Mesozoic has often been called the *Age of Reptiles*.

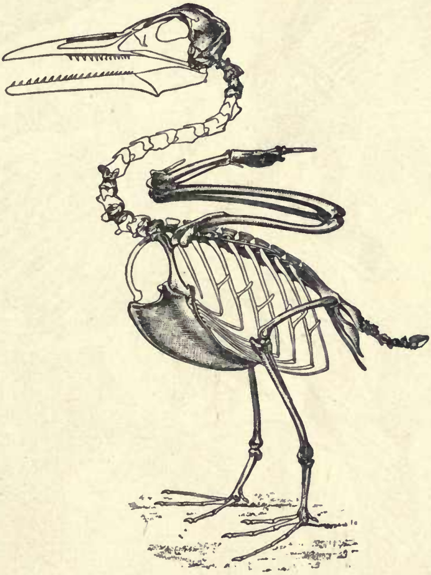

Fig. 189.—Restoration of *Ichthyornis victor* (Marsh). From the Cretaceous of Kansas (*U.S. Geo. Surv.*).

Many of the fossil-reptiles assumed grotesque forms, and some of them grew to a gigantic size. Among the best known are the *Palæosaurians* [2] or ancient lizards, of which the *Tuatara* (*Sphenodon punctatum*) of New Zealand is the sole living representative; *Plesiosaurians*,[3] *Ichthyosaurians*,[4] and *Deinosaurians*.[5]

The *Aves* or birds first appeared in the Mesozoic. Many have

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[1] Gr. *labyrinthos* = intricate, and *odous*, *odontos* = a tooth.

[2] Gr. *palaios* = ancient, and *sauros* = a lizard.

[3] Gr. *plesios* = near, and *sauros* = a lizard.

[4] Gr. *ichthus* = a fish, and *sauros* = a lizard.

[5] Gr. *deinos* = terrible, and *sauros* = a lizard.

lizard-like structure, and some of them have powerful beaks armed with teeth. Struthious birds of the ostrich, emu, and moa order have been found in the Lower Tertiary of Europe, and one from the London clay, called *Dasornis*, is considered by some to resemble the lately extinct *Dinornis* (moa) of New Zealand.

FIG. 190.—*Archæopteryx macrura.* (After Owen.)

The oldest fossil-bird is the *Archæopteryx*, from the Jurassic lithographic slaty limestone of Solenhofen, in Bavaria.

Mammalia.—This sub-kingdom includes the highest class of the vertebrata, and is characterised by the young being nourished for

To face page 285.]

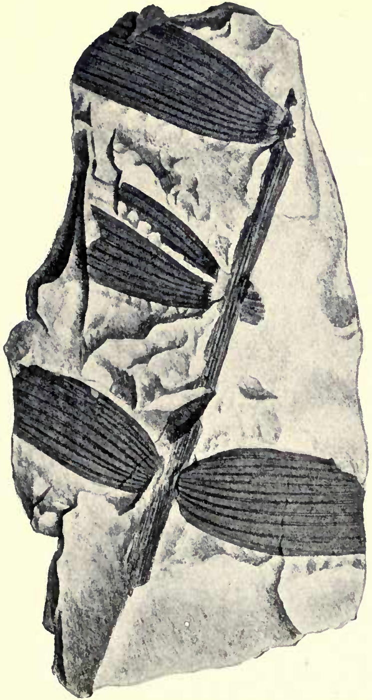

FIG. 191.—*Schizoneura australis* (Etheridge), showing straight venation of Monocotyledons or Endogens.

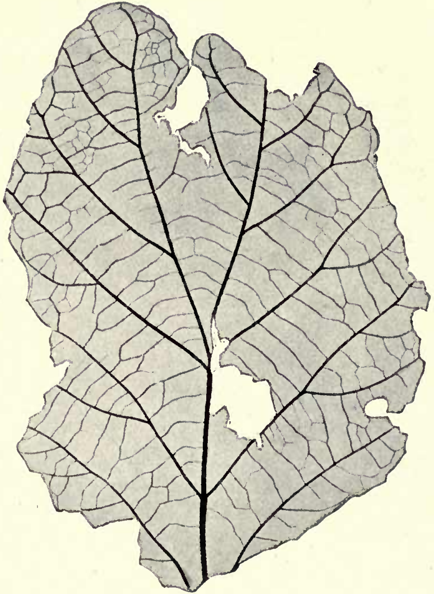

FIG. 192.—Leaf showing net-like venation of Dicotyledons or Exogens.

a longer or shorter time by milk or special secretion from the mammary glands.

The earliest evidence of mammals is met with in the Upper Trias, and in the Lower Jurassic the remains of small mammals become common. All the earlier forms are related to the existing Marsupials. In the Pliocene period the mammalian fauna assumes a modern appearance, comprising large tiger-like cats, bears, wolves, oxen, numerous antelopes, giraffes, deer, horse-like animals, and elephants. Most of the mammals of the Pleistocene belong to living genera.

The last group to appear includes the apes and man.

Vegetable Kingdom.

Plants are divided into two great groups :—

I. Cryptogamia [1] or *flowerless* plants.
II. Phanerogamia [2] or *flowering* plants.

The **Cryptogams** are typically represented by the *ferns*, *horse-tails*, *mosses*, *fungi*, *diatoms*, and *algæ* or *sea-weeds*. These are the oldest and lowest forms of plant-life.

The **Phanerogams** include all flowering plants which bear seeds, by means of which they reproduce themselves. They are subdivided into two groups as under :—

(1) *Gymnosperms*,[3] *i.e.* plants with naked seeds = *cycads* [4] or palms, and *coniferæ* or pines.
(2) *Angiosperms*,[5] *i.e.* plants with seeds enclosed in a seed-case or vessel = oak, walnut, and most forest trees (except pines); roses and most garden plants.

Of these two groups, the *Gymnosperms* represent the lowest types of flowering plants.

The *Angiosperms* are divided into two well-marked and easily distinguished groups as follow :—

Angiosperms { (*a*) *Monocotyledons*,[6] with one seed-lobe = grasses, cereals, etc.
(*b*) *Dicotyledons*,[7] with two seed-lobes = oaks, beans, peas, etc.

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[1] Gr. *kryptos* = hidden, and *gamos* = marriage.
[2] Gr. *phaneros* = evident, and *gamos* = marriage.
[3] Gr. *gymnos* = naked, and *sperma* = a seed.
[4] Gr. *kuka* = cocoa-palm.
[5] Gr. *angeios* = vessel, and *sperma* = a seed.
[6] Gr. *monos* = single, and *kotuledon* = seed-lobe.
[7] Gr. *di* = double, and *kotuledon* = seed-lobe.

The *Monocotyledons* usually possess hollow stems, and increase in size by *internal* growth and elongation at the summit, and hence are often called *Endogens.*[1]

The *Dicotyledons* possess a solid stem, and usually increase in size by the yearly addition of a new layer of wood on the *outside*, and hence are called *Exogens.*[2]

The leaves of the *Endogens* are generally distinguished by straight or parallel venation, and the leaves of the *Exogens* by reticulate or net-like venation.

The Palæozoic floras are mainly Cryptogamic, comprising ferns, mosses, algæ, and diatoms. The Middle Mesozoic floras, besides Cryptogams, include numerous coniferæ (pines) and cycads (palms). The Cretaceous and Tertiary floras are characterised by a predominance of Phanerogams.

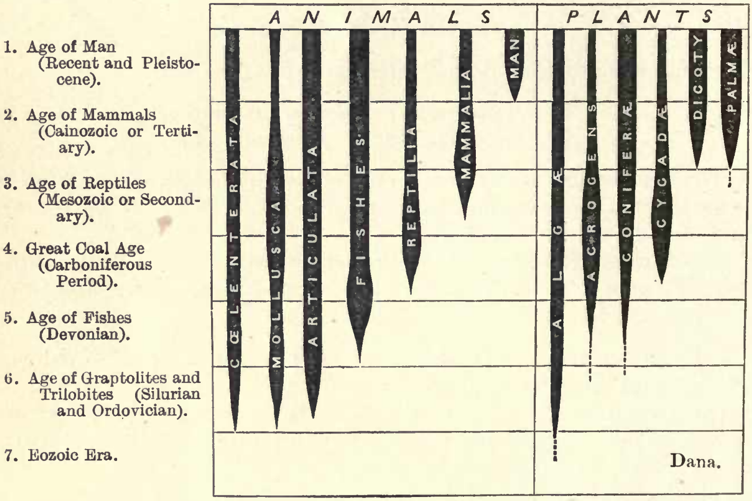

FIG. 193.

The above diagram approximately illustrates the progress of animal and plant-life throughout the geological record.

Uses of Fossils.

Perhaps the first and most obvious lesson to be gleaned from the study of fossils is the elementary truth that life, even in the earliest times, in its various functions and characteristics, differed in no way from the life of to-day.

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[1] Gr. *endon* = within, and *genes* = born or produced.

[2] Gr. *exo* = outside, and *genes* = born.

Further, we observe (*a*) that the lowly types of life that appear in the oldest rocks have persisted through all geological times up to the present day; (*b*) that new genera of progressively higher types suddenly appear as we ascend the geological scale; and (*c*) that many genera have a limited range in time.

From our knowledge of the distribution and habits of related existing faunas and floras, we have no difficulty in distinguishing terrestrial and marine organisms, or the inhabitants of warm and arctic seas, or the littoral from the pelagic.

Hence the fossils contained in a rock-formation form a permanent record of the climatic and physical conditions prevailing at the time the sediments which enclosed them were being deposited. They tell of the former existence of continents, rivers, lakes, estuaries, and seas; of tropical heat and arctic cold.

Fossils as Time-Registers.—As stratified rocks are composed of more or less parallel layers of sediment that were laid down one after another, it follows that the lower beds must be older than those that overlie them. This simple truth embodies what is called the *Law of Superposition*, and by means of it the geologist is able to determine the chronological order or succession of stratified rocks. The only exception to this law is when strata have been inverted by acute folding.

In the year 1790, William Smith, as the result of an examination of the Jurassic rocks of West England, established the fact that there was a regular order in the succession of the beds, and that each bed might be identified by its fossils. This apparently simple discovery gave a new direction to geological investigation. It laid the foundation of modern Stratigraphical Geology, and established a principle which at once raised geology to the status of a science.

Subsequent investigation has shown that not only are the larger groups of beds distinguished by particular genera and species, but that particular horizons or layers may possess forms that are limited to them, and are therefore distinctively their own.

The Lias is now known to be divisible into zones, each characterised by one or more species of Ammonite. In the same way the Ordovician may be divided into horizons or zones, each distinguished by one or more species of Graptolite limited to it. The same zonal distribution of fossils may be seen in the Chalk, and probably the same principle prevails throughout all the geological succession.

When once the order of succession of the strata in any region has been made out, the fossils found in the different beds become a valuable means of identifying the same, or contemporaneous, beds in other regions.

Lithological character alone is never a safe guide for the identification or correlation of distant groups of stratified rock. A group of beds may, like the Desert Sandstone of Queensland, present the same lithological characters over tens of thousands of square miles, and contain the same fossils throughout. Frequently, however, as already remarked in another chapter, a sandstone may pass in the same plane into a shale, and a shale into a sandstone. The sandstone and shale are *contemporaneous*, but lithologically they are very different rocks. Moreover, the fossils in these rocks will possess the same general *facies*, minor faunal differences that may exist being due to the different conditions of deposition.

When, therefore, the chronological succession of the stratified rocks of the globe has been established, and the distinctive fossils of each group identified, the fossils become *time-registers*, by which the age of distant rock-formations may be determined without regard to their lithological character. In other words, when the fossils of a rock-formation in a new region have been examined, the geologist will be able by their means to fix the age of the rocks relatively to the general succession.

Homotaxis.

Investigation has shown that the general succession of animal and plant life, throughout geological time, has been the same over the whole of the globe. For this similarity of succession Huxley adopted the biological term *homotaxis*.[1] For example, the genera of corals, graptolites, trilobites, fishes, reptiles, brachiopods, and plants that characterise the rocks of England, appear in the same general order in New Zealand; but it does not necessarily follow that because there is homotaxial parallelism that the groups of beds containing the same fauna in these distant lands are chronologically contemporaneous.

If the same organic types appeared simultaneously over the whole globe, it is obvious that all rocks containing the same fossils would be coeval. But this postulate is inconceivable. It is more probable that particular genera made their first appearance in the Northern, or in the Southern Hemisphere, and slowly spread by various processes of dispersion from one hemisphere to the other.

As would naturally be expected, the marine faunas would show a closer parallelism than the floras, a circumstance due to the greater facilities for rapid migration possessed by marine inhabitants in a continuous sea, compared with the slower dispersion of terrestrial organisms, perchance checked by physical obstructions, such as wide stretches of sea and mountain-chains.

During the process of dispersion, the genera would to some extent

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[1] Gr. *homos* = the same, and *taxis* = arrangement.

be modified by accidents of climate and changes in the distribution of land and water, arising from earth-movements; and the slower the rate of migration, the greater would be the differentiation.

But contemporaneity is in some respects a relative term. Recent events, that are separated by a year, seem far apart, while events that took place before the Christian era seem close together, even when separated by many decades. The geological day is not measured by years, and events possibly separated by thousands of decades of our limited chronology seem to converge when viewed in the distant perspective of geological time.

The marine faunas, on account of their greater opportunity for dispersion, have usually been taken as the basis of comparison and correlation throughout the geological record. If we regard the *genus* as the organic unit and not the *species*, which is merely the variant arising from adaptation to local environment, we cannot fail to be impressed with the extraordinary similarity of the marine types existing to-day in the corresponding latitudes of the two hemispheres. And when we find that the same correspondence of marine types, as between such widely separated regions as Western Europe and New Zealand, can be traced down through the Pliocene, Miocene, Eocene, Cretaceous, Jurassic, and Triassic formations without a break, or the interpolation of a fauna in one region that is not represented in the other, we are forced to conclude that in this portion of the geological record there is little room for chronological divergence. The parallelism of the more primitive Palæozoic faunas was doubtless as close, if not closer, than that of later ages.

The divergence of the successive land faunas of the two hemispheres might possibly be considerable in special areas in view of the greater opportunity for the survival of ancient types in regions isolated by deep seas, great mountain chains, or other geographical barriers.

The great Australian continent, on account of its permanency and isolation, is pre-eminently a land of survivals. Here we have a remarkable persistence of the marsupials—a primitive type of mammal—and an equally ancient type of flora.

SUMMARY.

(1) The remains of plants and animals that have been preserved in rocks are called *fossils*.

(2) Most fossils are sea-shells and other marine organisms. In many rocks, particularly in limestones and those composed of fine sediments, the original shell or calcareous covering of the animal is preserved; but in rocks of a porous character the shells have

frequently been dissolved away, leaving only an external or internal cast, or perhaps both.

(3) The rocks most frequently found fossiliferous are limestones, clays, marls, shales, and sandstones.

(4) The fossils are contemporaneous with the sediments or rocks in which they are enclosed. But a Cretaceous rock may contain blocks of stone that enclose Silurian fossils. Such fossils are called *derived fossils.*

(5) Igneous rocks do not contain fossils, but fossiliferous blocks of stratified rock are not uncommon among the fragmentary detritus ejected by volcanoes. Such blocks were doubtless torn from the sides of the volcanic vent.

(6) The most important fossils in the animal kingdom, beginning with the earliest and simplest forms, are foraminifera, graptolites, corals, sea-lilies, brachiopods, molluscs, fishes, reptiles, birds, and mammals ; and in the vegetable kingdom, ferns, mosses, horse-tails, cycads, pines, and forest trees related to existing types.

(7) The chronological succession of stratified rocks is determined by *superposition.* When the order of succession of stratified rocks has been determined, the contained fossils become of great value for the determination of the age of rock-formations in distant regions.

(8) The faunas and floras of geological time appear throughout the globe in the same orderly succession. Although genera may appear in the same order in the Northern and Southern Hemispheres, it does not necessarily follow that they are contemporaneous. Time would be required for dispersal from the cradle where the new genera appeared. But when a great succession of strata in widely separated regions contains faunas that appear in the same order in each region, we seem justified in assuming that although bed for bed the strata may not lie in precisely the same time-plane, for all practical purposes they are geologically contemporaneous.

CHAPTER XIX.

CONFORMITY AND UNCONFORMITY.

Conformity.—When a series of strata has been laid down in such a way that the stratification-planes are parallel with one another, the strata are said to be *conformable.*

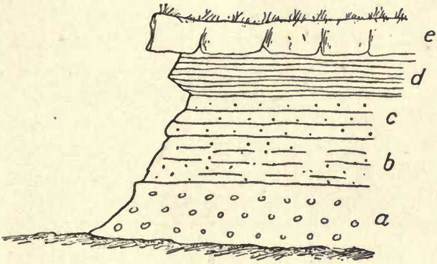

Fig. 194.—Showing conformable series of strata.

The meaning to be gathered from conformable stratification is that the deposition of the sediments composing the beds was continuous and uninterrupted, which is only another way of saying that no change of any moment took place in the physical geography of the area during the period covered by the deposition of the beds in question.

The beds may be laid down on a slowly sinking or rising sea-floor, and coarse sediments may be followed by fine, or fine by coarse, due to the overlap resulting from an advancing or receding shore-line, but the distinctive life of each zone will remain the same so long as the same physical conditions prevail.

Hence it is found that in a series of conformable strata there is no violent biological break or change in the character of the contained fauna, always provided that in a vast pile of sediments representing a great range of time, some of the older forms may disappear before the invasion of newer and more vigorous kinds of life in the uppermost strata.

Unconformity.—When a series of conformable strata rests on the upturned, folded, or denuded surface of an older series of beds, there is said to be an *unconformity* between the two formations. The younger series lies *unconformably* on the older.

In fig. 195 the younger series, *a*, *b*, *c*, rests unconformably on the upturned edges of the older series, *d*, *e*, *f*.

The meaning to be gathered from this relationship is that the older formation was deposited, consolidated, elevated, denuded, and again submerged before the younger formation was laid down. That is, the older area of deposition was elevated so as to form dry land, remained dry land for some time, and then became submerged before deposition once more began.

An unconformity is therefore an evidence of a *break* in the continuity of the geographical conditions which existed when the older formation was deposited. This break may represent a period of time of greater or less duration, depending on the rate of uplift, the length of time the raised sea-floor remained dry land, and the rate of the subsidence. That is, some unconformities may be slight, others very great.

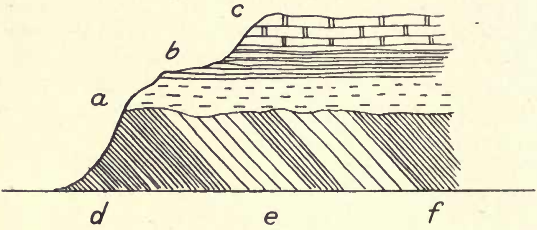

FIG. 195.—Showing an unconformity.

If the uplift is slow, the sediments as they emerge from the sea may be little disturbed in their stratification; and denudation may wear away only the upper layers before subsidence begins. In this case the unconformity will be slight, as the new sediments will be laid down with their bedding planes almost parallel with those of the older partially denuded formation.

But if the uplift is of long duration, permitting the land to be worn down by denudation to a surface of low relief before subsidence takes place, the newer sediments will be laid down on an approximately level surface of the older formations. In this case the older strata will be separated from the younger by a decided unconformity. When the older formation has been tilted or folded before the deposition of the younger, the unconformity may be as conspicuous as that shown in fig. 195 between points *d* and *a*; or in fig. 197 between *b* and *a*.

Unconformity is therefore a record of a change in the geographical conditions in the area of deposition.

A physical break, as might be expected, is usually marked by a diversity in the faunas of the unconformable rock-formations. It is obvious that the uplift of the sea-floor, after the deposition of the older sediments, must cause the migration or destruction of the existing fauna.

When submergence once more takes place and the deposition of sediments again commences, the new sea-floor will be peopled by colonists from the neighbouring seas. If the unconformity is slight, the incoming fauna will be the lineal descendants of the fauna displaced by the uplift; but if the unconformity is decided, the new fauna may possess little or no relationship to the old.

Evidences of Unconformity.—The most obvious proof is usually the discordance of the stratification-planes of the two formations. Moreover, as the older rocks were exposed to denudation before the deposition of the younger began, fragments and pebbles of the older rocks are frequently found in the younger.

Beds of conglomerate or grit in many cases form the bottom or basal members of a rock-formation. Hence they frequently occur at the break between two unconformable formations.

Thick beds of coarse conglomerate interbedded with shales or sandstones, although they do not indicate a physical break in the continuity of deposition, clearly mark a considerable change in the local geographical conditions arising either from elevation or subsidence.

When a younger series wraps around the edges of an older series, there is clear evidence of unconformity, even though no actual contact may be exposed between the two formations. Unconformity is also shown by the younger series overlapping the various members of the older.

Fault-fractures, mineral lodes or igneous dykes that are present in the lower formation, but end abruptly at a given point of contact, in other words do not penetrate the overlying series, afford convincing proof of interrupted deposition of sediments, and therefore of unconformity.

The fossil fauna of the different rock-formations is now so well ascertained that the unconformable relationship of two series of strata can be postulated even when no physical break is apparent. For example, when we find rocks with a Triassic fauna resting on Silurian strata, or rocks with a Tertiary fauna in contact with a Cretaceous system, we know that the Trias is unconformable to the Silurian, and the Tertiary to the Cretaceous, even if we are unable to trace the physical break in the field.

Interformational Unconformity.—Physical unconformity is sometimes seen in certain places between members of the same formation. Such discordance may have arisen from local uplift, or from the wash-out caused by tidal waves, temporary diversion of sea-currents, hurricanes, or cloud-bursts.

Deceptive Physical Conformity.—The actual line of contact between two rock-formations is rarely well exposed, being only seen to advantage in sea-cliffs, rocky gorges, and quarries. More often the junction-line is obscured with soil, loam, glacial drift, residual clays, or the peaty accumulations of forest or other vegetation. Care must therefore be exercised in the determination of the physical relationships of two adjoining formations, and in no case should final pronouncement be made on the evidence of one exposure.

Every formation represented in the geological record is distinguished by its own peculiar assemblage of fossil-remains, by means of which it can always be recognised, however complicated and obscure its stratigraphical relationships may be. Hence in the determination of relationships the palæontological evidence is of supreme importance.

Mere parallelism of the stratification-planes of two formations does not necessarily imply conformity. It may easily happen in the case of two systems not separated by a great interval of time, that steady uplift of the older to a height not far above sea-level in a region of quiet denudation, followed by steady subsidence, may result in the deposition of the younger in layers that rest on the older with apparent parallelism. Such deceptive conformity is found in South-East England and at Waipara, New Zealand, in Lower Egypt, as between the Cretaceous and Eocene; in Ireland as between the horizontal Trias and Upper Cretaceous near Belfast; and in South Africa, as between the Ecca Beds of Upper Carboniferous age and the Lower Cretaceous, as exposed at Worcester, in Cape Colony.

On the east side of the Libyan basin, the outcrops of the Upper Cretaceous and Lower Eocene limestones may be traced for scores of miles running parallel with one another and with the underlying quartzose Nubian Sandstone. At many places the inclination of the Cretaceous and Eocene is so nearly the same that no physical break can be detected between the two systems; while at other places the unconformity is quite distinct. Nevertheless the palæontological break is everywhere great.

It is obvious that when subsidence took place the old Cretaceous basin became an Eocene basin. When the tilting of strata takes place after the deposition of the younger beds, there may be little or no apparent stratigraphical break, except in places where the Cretaceous strata have been subject to considerable denudation.

In fig. 196 Tertiary beds are seen resting on the Cretaceous. As viewed near C and along section A—B, the two systems appear to be conformable, and the true relationship is only disclosed when the whole section from C to D is examined.

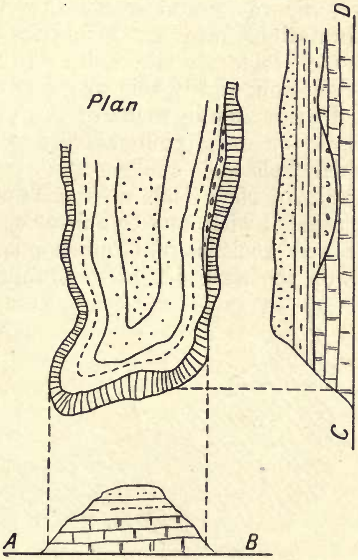

FIG. 196.—Plan and sections showing deceptive conformity.

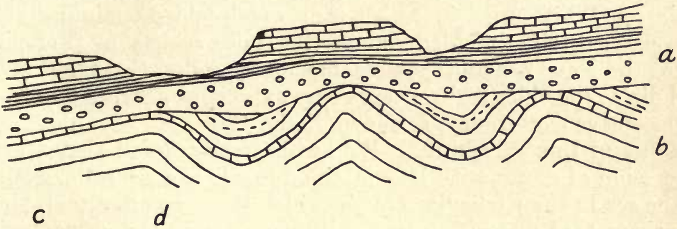

FIG. 197.—Showing deceptive conformity of two unconformable rock-formations.

Thus we see that the physical break between two systems may not be everywhere equally marked, and in some localities its detection may be impossible.

Moreover, there may be apparent conformity in places arising from accidents of folding or form of denudation. For example, in fig. 197 beds *a* are highly unconformable to beds *b* between points *b* and *d*, but between *d* and *c* there is apparent conformity.

Many notable examples of deceptive conformity are found in regions where *orogenic* or mountain-building movements have thrust the rock-formations into great folds. All the stratified rocks involved in such folds are tilted so as to run parallel with the main axes of elevation, and in this way a parallelism of stratification is obtained even among rocks of the most diverse ages. In this way Triassic or even younger formations may appear conformable to older Palæozoic rocks.

In the alpine chain of New Zealand, the Trias rocks are overfolded so as to be parallel with, and to appear conformable to, the underlying schists and gneisses of Cambrian age; while in the Bernese Oberland, on the west side of the Jungfrau, the strips of Eocene nummulitic limestone appear to be conformable to the Malm or White Jura in which they are infolded. Similarly the Lower Tertiaries infolded among the mica-schists at Moonlight Creek in New Zealand possess for many miles the same strike and dip as the older rocks, everywhere exhibiting a striking example of deceptive conformity, as shown in fig. 198.

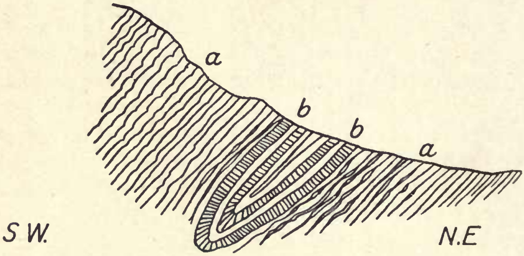

FIG. 198.—Showing deceptive conformity due to involvement of Tertiaries among older Palæozoic mica-schists, Moonlight Creek, New Zealand.
(*a*) Mica-schist. (*b*) Tertiaries.

Value of Unconformities.—We have already found that a great succession of strata with its contained fossils is a record or history of the sea in the particular area in which the deposition took place. It proves that deposition was *continuous*, hence the chronological importance of such a succession.

But an unconformity is no less valuable. It tells us of a *break* in the continuity of deposition arising from the uplift of the sea-floor whereby the previously existing area of denudation was augmented. It fixes the dates of earth-movements, and enables us to outline approximately the form of the land-areas and sea-margins in past geological times.

The obvious effect of the uplift of the sea-floor with its newly formed sediments will be to increase the previously existing area of dry land, thereby increasing the area of denudation. Denudation will still be as active as ever, and its products will be deposited on the new sea-margin which, before the uplift, may have been the floor of a deep or shallow sea.

From this we gather that unconformities are not necessarily world-wide, for though uplift may cause deposition to cease in a particular area, its ultimate effect is merely to shift the scene of deposition to some other portion of the sea-floor. Therefore by tabulating the various series of strata and the unconformities in some island or continent, we are able to tell when that area was submerged and when it was dry land. The breaks, or lost chapters, as unconformities have been aptly called, can only be filled in by the study of some area where deposition was continuous.

In some continents the geological record is almost complete; in others it is broken and imperfect. A full record tells us that the area was marginal to some land of great permanence that may have been subject to oscillations, but was never completely submerged, being an area of denudation, though perhaps of constantly varying form, from the earliest geological times.

A region containing an imperfect record is an area of still greater permanence, for its persistence as dry land is the main cause of the imperfection of the record, for obviously while it remained dry land it could not be an area of deposition.

But all portions of a continent are not equally stable, as shown by the circumstance that the record may be comparatively complete in one portion and scanty in another.

Changes of Life during Geological Time.—It is sometimes found that the same or closely related types persist through a considerable thickness of strata, which may be partly due to the rapid accumulation of the sediments, and partly to the continuance of the same physical conditions of deposition.

In other cases changes in the fauna occur in every few feet of rock, which would tend to show that the rate of deposition was relatively slow compared with the organic changes in the fauna. This rapid change of faunal types is met with in many fine-grained shales and in certain cherts, all of which would appear to have accumulated slowly in deep water far from land.

In a pile of conformable strata consisting of basal conglomerates followed by sandstones, clays, and limestone, the basal rocks will be distinguished by the prevalence of littoral shells. If a band of conglomerate follows the clays, there will in all probability be a reappearance of the prevalent types of the lower conglomerate; and if this conglomerate is followed by clays, these will probably contain many of the dominant types of the lower clays. In other words, with a recurrence of the same conditions of deposition, there is frequently a reappearance of the same faunal types by migration from the neighbouring seas. Just how much these types are modified will depend on the lapse of time represented by the intervening strata.

Some forms of life, like the Nautilus and Shark, have a great vertical range in geological time; while others, like many species of Ammonites and Belemnites, have a wide geographical distribution in some particular horizon or time-plane, but a limited vertical range.

The chronological classification of the stratified rock-formations is mainly based on the interpretation of the physical breaks and the progressive organic changes observed throughout the geological record. The rocks are the monuments, and the fossils the hieroglyphics, by means of which the geologist is enabled to divide the history of the Earth into eras, periods, and epochs, and to unravel the successive physical and organic changes that have taken place since the beginning of geological time.

Permanence of Continents.—It has now been established as geological axioms :—

(*a*) That stratified rocks are composed of detrital material derived from the denudation of land areas ;

(*b*) That stratified rocks are marginal to the land from which the material composing them was derived.

The obvious inference to be drawn from these simple truths is, that the continents, though constantly varying in size, shape, and height, through subsidence and uplift, have existed as land areas from a remote geological period.

It would almost appear as if the present continents and deep seas were developed by the first crumpling of the Earth's crust, arising from cooling and contraction, at some period long antecedent to the formation of the oldest known stratified rocks.

The continents have been subject to denudation throughout all time, and the younger stratified formations have been derived from the waste of the older. The same material has appeared re-sorted in different rock-formations in different geological ages. The continents have been wasted while being reconstructed, and have thereby been preserved from destruction by the continual accumulation of new material supplied from their own ruin. In this way they have maintained their individuality.

The preservation of the continents has been solely dependent on oscillations of the land. For it is obvious that if the continents had remained stationary, let us say, since the close of the Palæozoic, neither rising nor sinking, they would in the course of time have been reduced to a plain of marine denudation. They would eventually have disappeared beneath the surface of the sea, and ceased to exist as land-areas. Deposition would then have come to an end, and from then onward there would be a complete blank in the geological succession, and a cessation in the progressive development of all animal and vegetable life.

Uplift and denudation are doubtless responsible for the incompleteness of the geological record, but it is certain that without continual oscillation and deposition there could be no succession of stratified rocks and therefore no record of organic life.

SUMMARY.

(1) When sediments are laid down on the floor of the sea or a lake in layers that lie parallel with one another, they are said to be *conformable*. The bottom layers will be older than the upper, but there will be no break in the continuity of the succession.

(2) When a series of sediments is uplifted so as to become dry land and is subjected to denudation in such a way that its surface becomes worn into hollows and ridges, eventually submerged and then covered with a succession of sediments, the new sediments are said to be *unconformable* to the older underlying series.

When the older series of beds is not only eroded but also tilted by Earth-movements before the younger series is laid down on it, the unconformity is considerable, and probably represents a long interval of time between the deposition of the two series.

(3) An unconformity marks a physical break in the continuity of the local conditions of deposition. The uplift which preceded it causes a migration of the marine fauna to adjacent seas. If the uplift lasted a considerable time, there may be recognisable change in the character of the fauna when submergence once more permits deposition to begin in that area.

(4) All stratified rocks are marginal to continental areas, and all are composed of material derived from the waste of older rocks. From this it is inferred that continents, though constantly varying in size and shape due to oscillations, have existed from the remotest geological times.

PART II.

CHAPTER XX.

HISTORY OF THE EARTH.

Division of Geological Record.

When studying an ancient language, the student as a first step must acquire a knowledge of the form of the written characters, of the significance of each character standing by itself, and of the meaning to be attached to a number of the characters when placed together. And so it is in geology. The study of rocks and the geological processes involved in the formation of rocks; of fossils, and the preservation of fossils, is the preliminary but necessary preparation that must be undertaken before we can successfully read the past history of the Earth as presented in the geological record. In geology the rocks are the monuments, the fossils the records; and when we have acquired a working knowledge of the A B C of the science, we are able to interpret the writing which unfolds a fascinating story of sunshine and shower, of brooks and rivers, of lakes and seas, of jungle and forest, of deserts and swamps, of volcanoes and earthquakes. Moreover, we further discover the wonderful procession of life that has peopled and clothed the Earth throughout the geological ages.

The geological history of the Earth from the earliest times is a record of uplift and subsidence, of retreating and advancing seas, of denudation and deposition.

During subsidence the sea advanced on the land, and the conditions of deposition that prevailed were marine. During uplift the sea retreated, and large inland seas and basins were enclosed, and in these the conditions of deposition were lacustrine or terrestrial. Frequent alternations of uplift and subsidence, commonly spoken of as oscillations of the land, often led to the deposition of alternating marine and terrestrial beds.

Uplift increased the size of the continents and consequently augmented the area of land exposed to denudation. Conversely, subsidence diminished the area of the dry land exposed to denudation.

The Gaps in the Record.—The history of the Earth must be read from the story of the rocks and their *fossil contents* in the same way as ancient Egyptian history is interpreted from the different types of sculpture and pottery buried in the successive layers of debris that cover the sites of the ancient cities and temples. On some sites we find evidence of unbroken occupation through a long succession of dynasties, in others there are wide gaps that mark periods of desertion and ruin. And so it is with the geological record. In some regions the succession is relatively complete, in others it is fragmentary and full of gaps. In most continents the geological record is incomplete, but fortunately the gaps in the different regions do not always coincide, or occur in the same place in the succession ; hence we are able by a bit of patching to build up a record that, while admittedly imperfect, nevertheless affords a valuable synopsis of the physical geography and life of the Earth from the remotest times.

Before we proceed further, let us clearly understand what is meant by gaps in the stratigraphical succession. In one part of a continent, the Palæozoic formations may be well represented and followed directly by the Tertiary formations resting on a highly denuded surface of the older rocks. Here we have a gap or unconformity representing the whole of the Mesozoic era ; and from this we gather that one of two things has happened. Either the sea-floor in this region was uplifted after the close of the Palæozoic and remained dry land throughout the whole Mesozoic era, thus preventing the deposition of sediments, or else deposition was continuous for a portion of the Mesozoic, but the sediments thus formed were swept away by denudation during an interval of uplift before the deposition of the Tertiaries began. So far as the geological record is concerned, the result is a complete blank from the close of the Palæozoic to the beginning of the Tertiary era.

In another portion of the same continent we may find the Palæozoic rocks followed in orderly succession by all the Mesozoic formations ; hence, when we make up the stratigraphic succession for the whole continent, we are able to show a complete record.

The gaps in the stratigraphical succession in any given region are due either to sweeping denudation prior to the deposition of the younger unconformable strata, or to uplift, which prevented the deposition of sediments.

Uplift does not always take place at a uniform rate over a whole continent. One border may rise more rapidly than another, thereby affording an example of what is called *differential uplift.* Or one side of a continent may rise and the other sink, the movement resembling the tilting of a plank laid across a beam. In this case sediments will be deposited on the sinking sea-floor; while, on the uplifted side, not only will there be no deposition of sediments, but the strata newly raised from the sea will be worn away, thereby accentuating and widening the gap that will exist before subsidence once more permits deposition to take place in that area.

Deposition of sediments has been continuous around the shores of the continents ever since they came into existence; but the sediments have not accumulated as a continuous pile in any one place on account of the frequent oscillations of the land.

Uplift does not cause a complete cessation of deposition everywhere, for it is obvious that while dry land and seas exist, the products of denudation must be carried to the sea. Therefore, although uplift may cause a cessation of deposition in one place, its general effect is merely to shift the scene of deposition to the adjacent seas. Hence it is that gaps in the succession in one place are represented by sediments laid down in some other area. But the sediments that should fill the gaps have not always been preserved, or if preserved, they are not accessible. In some regions they have been removed by denudation, in others they have become obscured in earth-folds or submerged beneath the sea. Hence it happens that with all the patching that research has made possible, there still remain many gaps in the stratigraphical succession that cannot be filled.

Even if the stratigraphical succession were complete, it is certain that the record of life contained in the rocks would still be imperfect, for we know that only a small proportion of the organisms that lived in past times have been preserved as fossils. Our knowledge of the marine faunas is very imperfect, and of the land faunas, meagre and fragmentary, the opportunity for preservation of terrestrial animals being small compared with that of organisms living in the sea.

Unconformities represent gaps in the succession of stratified rocks during which there is no record of the contemporaneous fauna and flora. An unconformity is merely a lapse of time of which there is no local record. It does not measure the interval, the duration of which can only be demonstrated by the fossil evidence.

When the characteristic fossils of the geological record have once been determined, the fossil evidence may prove the existence of gaps where they are not physically apparent. That is, deceptive conformity can frequently be proved by the fossil evidence.

The Geological Record.—Superposition is the only basis of stratigraphical succession.

The order in which the different layers of debris occur on the site of a buried city is of greater importance than the remains of pottery and works of art found in each layer, for obviously it is only after the proper order of succession of the different layers has been ascertained and verified that the contents become of chronological value. When the order of stratigraphical succession of a pile of strata has been definitely ascertained, and the characteristic fossils of the different beds determined, the fossils at once possess a chronological value and become useful for the fixing of the age of strata in distant regions.

It is now known that certain fossils occur only in certain groups of beds, and advantage has been taken of this truth to divide the geological record into *eras*, *periods*, and *epochs*, in the same way as historic time is divided into empires, dynasties, and reigns, or as a book is divided into chapters, paragraphs, and sentences. It is well to remember that the subdivision of geological time is only an empirical arrangement intended to facilitate the study and investigation of the past history of the Earth as revealed by the stratified rocks and their fossils.

Stratified rocks are arranged in *groups* which are subdivided into *systems* which in turn consist of *series*. In many cases a *series* is divided into *stages*, *i.e.* upper, middle, and lower divisions; and sometimes a stage is found to consist of recognisable *zones*, each characterised by distinctive fossils limited to it.

The equivalent divisions of time corresponding to groups, systems, series, etc., are as follow:—

Analogy.	Geological Time.	Strata.	Example.
Book, .	Era	=Group,	*e.g.* Mesozoic Group.
Chapter, .	Period	=System,	*e.g.* Cretaceous System.
Paragraph, .	Epoch	=Series,	*e.g.* Chalk.
Sentence, .	Age	=Stage,	*e.g.* Upper Chalk.
Line, . .	Stage	=Zone,	*e.g.* Zone of *Belemnitella mucronata.*

When we speak of the *Cretaceous Period* we refer to a particular interval of geological time; but when we speak of the *Cretaceous System* we have in mind the assemblage of strata formed in the Cretaceous Period.

Geological time is divided into four grand *eras* or books, which are separated by unconformities or by great palæontological changes in the fauna and flora. Each book is subdivided into chapters or *periods*, and each chapter into paragraphs or *epochs*. In each paragraph there may be one, two, or more sentences or *ages*, and each sentence may consist of one or more lines, i.e. *time-planes* or *stages*.

Epoch.	Period.
Cainozoic or Tertiary.	Recent.
	Pleistocene.
	Pliocene.
	Miocene.
	Oligocene.
	Eocene.
	Palæontological Break.
Mesozoic or Secondary.	Cretaceous.
	Jurassic.
	Triassic.
	Palæontological Break.
Palæozoic or Primary.	Permian.
	Carboniferous.
	Devonian.
	Silurian.
	Ordovician.
	Cambrian.
	Unconformity.
Eozoic or Archæan.	Algonkian or Torridonian.
	Unconformity.
	Laurentian or Lewisian.

Such terms as Permian, Devonian, etc., are time-names and cover vast æons. When a rock is said to be of Miocene age, a reference to the table will show that it is comparatively young; whereas a rock of Silurian age is one of great antiquity.

Some of the names of the periods are lithological, as Cretaceous and Carboniferous; some have a numerical origin like Trias; but the majority are derived from the names of the localities or regions where the rocks of that particular age are typically developed. The last, which are the best adapted for general use, comprise Cambrian, Silurian, Devonian, Permian, and Jurassic, which are names generally adopted by all geologists. But whatever their origin, it must always be remembered that these names have no lithological significance. The Silurian period, for example, is merely an interval of time, and the rocks ascribed to it in one place may consist of conglomerates, sandstones, and shales; in another of limestones, shales, etc.

Further, the periods do not represent equal intervals of time any more than the reigns of the kings in history.

Geological time cannot be measured in years. All attempts to gauge the age of the Earth since it became habitable on the basis of the rate of deposition of sediments in deltas and estuaries have ended in failure. All that can be safely hazarded is that the Tertiary era may cover several million years, and the whole geological record perhaps scores of millions.

Summary.

(1) The primary object of the study of rocks, fossils, and geological processes is to enable the student to unravel the past history of the Earth.

(2) The unconformities or gaps in the geological record are intervals not represented by sediments. The gaps may be due to uplift, or to denudation, or to both. When no sediments are laid down, there is no record of the fauna or flora of the interval covered by the unconformity; consequently stratigraphical unconformity is usually marked by a palæontological break.

Unconformities do not measure time. The intervals they represent can only be estimated in a relative way from the extent of the break in the succession of life.

(3) Superposition is the only true basis of stratigraphical succession. When the order in which the rock-formations occur has once been determined, the fossils contained in them become of great value in fixing the age of rocks in distant regions. But since the succession of organic types throughout the geological record has been definitely ascertained and is the same in all parts of the globe, fossils are of great value in fixing the age of strata wherever they occur, or however involved they may be in crustal folds.

(4) The different groups of strata are characterised by certain distinctive fossils, and advantage has been taken of this to subdivide geological time into eras, periods, and epochs.

(5) The periods are not of equal length any more than the reigns of the kings of history. Moreover, the time that has elapsed since the Earth became habitable cannot be estimated in years, but is vast and may possibly amount to many score million years.

CHAPTER XXI.

EOZOIC[1] ERA.

THIS group includes all the rocks of pre-Cambrian age that reach the surface or have been laid bare by denudation.

The Eozoic rocks are not only the oldest and thickest, but also the most widespread of all the rock-formations taking part in the structure of the Earth's crust. Even where not exposed at the surface, it may safely be assumed that they form the basement on which all the younger formations rest.

In North America these ancient rocks occupy an area of nearly 2,000,000 square miles, and have an estimated thickness of over 50,000 feet. Elsewhere they occur in numerous isolated patches, some of considerable extent in the British Isles, Scandinavia, Bohemia, Alps, Himalayas, China, Andes, Australia, and South Africa.

The distinguishing features of these primitive rocks are :—

(*a*) Their universal extent.
(*b*) Their vast thickness.
(*c*) Their highly metamorphic character.
(*d*) Their poverty in fossils.
(*e*) Their richness in valuable ores and minerals.

The time covered by the formation of the pre-Cambrian systems must have been of extraordinary length, probably as long as the Palæozic, Mesozoic, and Cainozoic eras put together.

In the Lake Superior region of North America where the Eozoic has its greatest and perhaps most typical development, the succession recognised by American geologists is as follows, the name Archæan being restricted to the lower highly crystalline complex of altered rocks :—

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[1] Gr. *eos* = the dawn, and *zoe* = life.

Pre-Cambrian.

Algonkian	(1) Keweenawan (Copper-bearing series).	
	Unconformity.	
	(2) Huronian.	Upper.
		Unconformity.
		Middle.
		Unconformity.
		Lower.
	Unconformity.	
Archæan	(3) Keewatin.	
	Eruptive unconformity.	
	(4) Laurentian.	

Archæan.[1]—The greatest and perhaps best known development of rocks of this age, occurs in the Laurentian region; but they are well represented in the British Isles, and in all the great continents.

Characteristically they consist of granites, gneisses, and various schists, with which are sometimes associated various clastic and pyroclastic rocks, usually highly altered. No trace of organic remains has ever been found in them, and this circumstance led the geologists of last century to call them *Azoic*,[2] a term at one time loosely applied to all rocks older than the Palæozoic.

Laurentian Region.

The Archæan rocks of this region are easily divisible into two great formations, namely, the *Keewatin* schist formation and the *Laurentian* granitic and gneissic complex, which is in some places intrusive in the rocks of the Keewatin, but does not reach into the Cambrian.

Keewatin.—The lower Archæan of North America consists mainly of crystalline schists resulting from the metamorphism of igneous rocks that would seem to have been principally surface flows, tuffs, and pyroclastic sediments. Associated with the altered lavas and pyroclastics, there are subordinate beds of conglomerate and shale, which are the oldest sedimentary rocks of which there is any record.

Intercalated with the aqueous rocks, there are lenticular beds of jasper and iron ore.

The more abundant metamorphic rocks are hornblende-schist, greenstone-schist, and mica-schist, which are everywhere sharply

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[1] Gr. *archaios* = very old.

[2] Gr. *a* = without, and *zoe* = life.

folded, plicated, and sheared. They have been at many different times intruded by plutonic igneous rocks on a scale not equalled in any other period of the geological record.

The thickness of the Keewatin system amounts to many thousand feet, but the rocks are so complicated with folding, shearing, and intrusives that it is difficult to make a trustworthy estimate.

The massive surface flows and tuffs of which the schists of this period are mainly composed indicate the existence of older rocks below them; and the presence of sedimentary rocks implies denudation and contemporaneous deposition. Of the extent of the pre-Archæan land over which the Keewatin volcanoes spread such vast piles of lavas and tuffs, or of the seas in which the sedimentaries were deposited, nothing whatever is known.

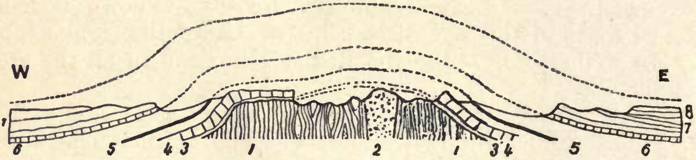

FIG. 199.—Ideal cross-section of Black Hills. (After Henry Newton.)

The vertical scale is about six times the horizontal; the dotted lines indicate the portion of the uplift removed by erosion.

1, Archæan slates and schists.
2, Granite.
3, Cambrian resting unconformably on 1 and 2.
4, Carboniferous.
5, Red beds, with included limestones.
6, Jurassic.
7, Cretaceous.
8, White River Tertiary resting unconformably on 7.

No authentic traces of life have so far been found in the Archæan, and this is perhaps not surprising when we consider the subordinate part played by the sedimentary rocks and the intense metamorphism they have suffered. Moreover, it is not improbable that the sedimentaries we now see are but the remnants of piles of clastic rocks that were deposited, consolidated, elevated, and destroyed long before the advent of the Palæozoic era. There is nothing to prove that life did not exist in these remote times. On the contrary, the denudation of the dry land by aqueous agencies, and the deposition of sediments, indicate the prevalence of the physical conditions that we usually associate with life.

The earlier pages of historic time are notoriously fragmentary, blurred, or missing; hence it should cause us no surprise to find the first pages of the geological record even more incomplete, dim, and difficult to interpret.

Laurentian.—The rocks of this great system consist of granites and gneisses that have been intruded into the Keewatin as dykes and great bosses, or which occur as the country-rock, covering large areas. At one time the Laurentian was considered to be a distinctively basal granite complex, but wherever it comes in contact with the Keewatin, it is found to be intrusive; hence it must be younger than the Keewatin.

The gneisses include ordinary granitic gneiss, syenite-gneiss, and diorite-gneiss, all of which are deeply involved among the granites. Their origin is still obscure. By some writers they are regarded as highly metamorphosed sedimentaries, by others, as foliated and altered eruptives.

Fig. 200.—Hypothetical section across the Menominee iron region in the vicinity of Quinnesec Valley. (After R. D. Irving, 1890.)

A, Basal sericitic quartz-slates.
B, Quartzite.
C, Limestone.
D, Iron horizon.
E, Slates and quartzites.
G, Granite.
Sch., Schists of the Laurentian.

The second view is the one most favoured by petrographers.

Algonkian.—This group includes most of the North American pre-Cambrian sedimentaries, many of which are highly metamorphosed, folded, and contorted. It is associated with masses of igneous rock, also much altered and folded.

The rocks are principally conglomerates, sandstones, shales, quartzites, limestones (often graphitic or dolomitic), various schists, gneisses, and granites. Their thickness is probably not less than 40,000 feet.

In the Lake Superior region where the succession is best seen, the Algonkian may be divided into four distinct systems that are separated by well-marked unconformities:—

(*a*) Keweenawan.
(*b*) Upper Huronian
(*c*) Middle Huronian
(*d*) Lower Huronian } Algonkian.

The largest area covered by the Algonkian is that of the Belt Series of Northern Montana, Idaho, and South British Columbia.

Fossils have been reported from many places, but in most cases they have been found on close examination to be of inorganic origin. Only in two instances are true fossils known in the pre-Cambrian areas of the United States, namely, in the shales of the Belt Series of Montana, and in the Chuar group of the Grand Canyon. These represent the earliest forms of life yet found.

The fauna of the Algonkian Montana shales includes four species of annelid trails, and trails that appear to have been made by a minute mollusc or crustacean. The same shales also contain thousands of fragments of one or more genera of crustaceans.

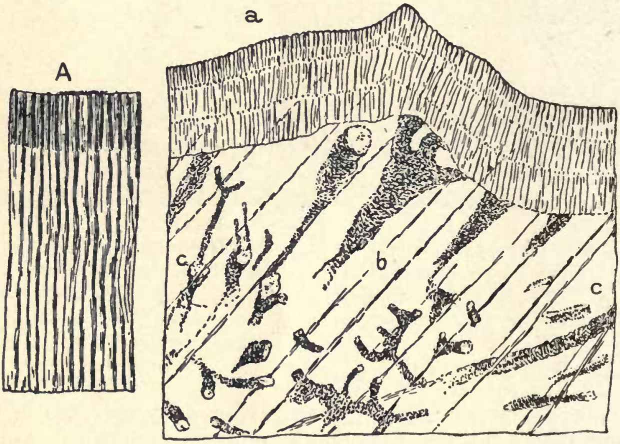

Fig. 201.—Portion of *Eozoon* magnified 100 diameters, showing the supposed original cell-wall with tubulation and the supplemental skeleton with canals. (After W. B. Carpenter.)

(*a*) Original tubulated wall or "Nummuline layer," more magnified in Fig. A.
(*b c*) Intermediate skeleton with canals.

The fossils of the Grand Canyon Algonkians are a small discinoid shell and a *Stromatopora*-like form.

The discovery by Logan in 1863 of certain forms in the Algonkian limestones of Canada and the Adirondacks of New York, which he thought were of organic origin, led to a controversy which lasted nearly forty years. Specimens from the base of the "Grenville limestone" weres ubmitted to J. W. Dawson, who, in 1865, recognised them as organic, and referred them to protozoans related to the foraminifera. On account of their geological position he named them *Eozoon canadense.*

W. B. Carpenter, the microscopist, confirmed the conclusions of Dawson; but William King and T. H. Rowney of Queen's University, Ireland, challenged the organic origin of Eozoon, and affirmed their belief that the imitative structures were purely mineral and of crystalline origin resulting from chemical change.

Similar structures were about this time found in Bavaria and elsewhere. The view of King and Rowney was subsequently supported by Mœbius of Kiel, J. W. Gregory, and H. J. Johnston-Lavis.

It is now generally believed that *Eozoon canadense* is of mineral origin.

Pre-Cambrian rocks represented by numerous isolated patches of granite, gneiss, and crystalline schists are exposed at the surface in all the continents. They form the framework of all the great mountain-chains, and also appear in the truncated arid plateaux of Africa, Asia, and Australia, and in the stumps of some worn-down or sunken chains of great antiquity.

In many regions there is little or no available data as to the age of the rocks. The general practice almost everywhere is to refer all gneissic and schistose rock-formations of unknown age to the Archæan. At the present time the information as to the general character and succession of the pre-Cambrian rocks is so meagre that no satisfactory basis for their correlation with the Eozoic of North America has yet been worked out. A resemblance in some of the broader features is, however, becoming apparent in many instances. The pre-Cambrian of Europe, for example, is characterised by a basal complex of schist, gneiss, and granite, unconformably overlain by a highly altered series that is mainly sedimentary and devoid of recognisable fossils. The former may, in a general way, be correlated with the Archæan, and the latter with the Algonkian.

British Isles.—Pre-Cambrian rocks are well exposed in the North-West Highlands of Scotland; and in Donegal, Mayo, and Galway Counties, in North and West Ireland. Smaller patches of these rocks crop out in Anglesey; at the Longmynd and the Wrekin in Shropshire; at Malvern Hills and St David's in Pembrokeshire; and at Charnwood Forest in Leicestershire.

The area occupied by these rocks in Scotland is the largest and most important in the British Isles, and although relatively small when compared with the Eozoic tracts of North America or Scandinavia, there is perhaps no part of Europe where they are so well displayed, or where they have been the subject of more critical examination.

Mainly as the result of the researches of Peach and Horne, they have been divided into two well-marked systems, namely, the

Torridonian, dominantly sedimentary; and the *Lewisian*, a basal complex of crystalline schists, gneisses, and granites.

Pre-Cambrian
- I. *Torridonian.*—Comprising a thickness of 8000 or 10,000 feet of sandstones, shales, grits, and conglomerates, with subordinate calcareous bands.

  Great unconformity.
- II. *Lewisian.*—Mainly gneisses, of probably igneous origin, and crystalline schists, which may be altered sedimentaries.

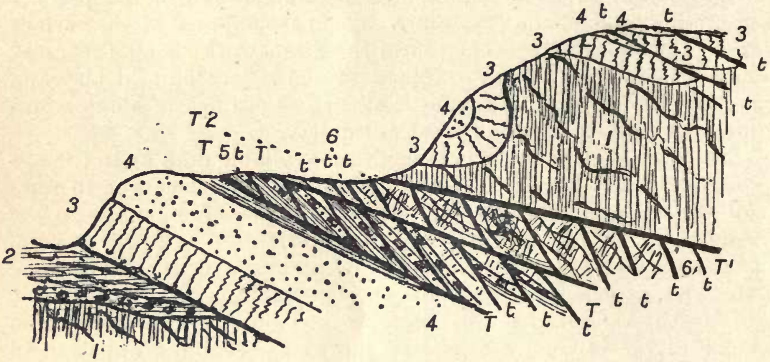

FIG. 202.—Diagrammatic section of west face of Glasven. Hor. dist. = 1½ mile. (After Peach and Horne.)

1, Gneiss covered by Torridon sandstone (2); 3, Cambrian quartzite; 4, Pipe-rock followed by fucoid bed (5), and the limestone (6).

T, T^1, T^2, powerful thrust-planes; *t*, *t*, minor thrusts.

Lewisian.—This great system, which may very well be correlated with the Archæan of North America, forms the Isle of Lewis, from which it takes its name, and extends throughout the Outer Hebrides, whence it passes on to the mainland.

The characteristic rocks are gneisses and crystalline schists that are frequently closely folded and contorted, and in places penetrated by numerous igneous dykes.

Generally the rocks are so much altered that it is impossible to make much of their original character; but where they are less altered, they are seen to pass into syenites, diorites, gabbros, and other plutonic igneous rocks.

In the valley of Loch Maree there is a remarkable series of metamorphic rocks consisting chiefly of mica-schist, quartz-schist, graphite-schist, and limestone, for which Sir Archibald Geikie has proposed the name *Dalradian*. This group is probably sedimentary; and it appears to be intruded by the Lewisian gneiss. If this relationship be verified, the Dalradian[1] must take its place as the oldest group of rocks in Britain, if not in Europe.

Torridonian.—The rocks of this system, like the American Algonkian, are typically sedimentary. They rest on a highly denuded surface of the Lewisian, from which they are separated by a great unconformity.

The Torridonian system extends as a belt along the west coast of Scotland for a distance of 100 miles, and take its name from Lake Torridon, where they are typically displayed. The lowest bed is a conglomerate which contains fragments of Lewisian gneiss, and also pebbles of unaltered igneous rocks that are unknown in the Lewisian of Scotland, but resemble some of the Archæan lavas in Shropshire.

The upper portion of the Torridonian is composed of red and chocolate-coloured sandstones that appear to have been formed in desert or continental conditions.

A characteristic feature of the North-West Highlands of Scotland is the remarkable horizontal shearing of the overlying Cambrian rocks, which have been fractured and deformed by a series of powerful thrust-planes, the most easterly and greatest of which, called the *Moine Thrust*, has carried the strata overlying it westward for a distance of at least ten miles on to the undisturbed Cambrian rocks.

Pre-Cambrian of other Countries.—The largest continuous tract of pre-Cambrian rocks in Europe occupies Scandinavia, and passes into Finland. The rocks are principally granites, gneisses, and crystalline schists, with which are associated bands of limestone.

The Algonkian and Archæan divisions of the pre-Cambrian are recognised in France; but in Central Europe the rocks have not been subdivided.

Two series of gneisses have been recognised in Northern India; and in China, where there is a great development of gneiss, schists, quartzites, and limestone of pre-Cambrian age, the succession, as worked out by Willis, shows a singular resemblance to that of North America.

In Australia and New Zealand there are extensive tracts occupied by massifs of granite, gneiss, mica-schist, and limestone, frequently much folded and plicated, faulted, and sheared, and in many places intruded by numerous igneous dykes. The age and relationships of these rocks to lower Palæozoic formations have not yet been worked out.

The evidence as to the great antiquity of the rocks reputed to

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[1] So named after the old Celtic Kingdom of Dalradia in North Ireland.

be pre-Cambrian is not always satisfactory, and is only capable of proof where the older Palæozoic formations are present. Detailed geological surveys have, in the past few decades, greatly reduced the areas formerly ascribed to the Archæan, and in all probability future observations will still further reduce their extent.

ECONOMIC MINERALS.

The crystalline rocks of pre-Cambrian age are everywhere remarkable for their richness in metallic ores and precious stones.

The famous copper deposits of Lake Superior, and the vast bodies of iron ore in the same region, occur in the Keweenawan and Huronian divisions of the Algonkian respectively.

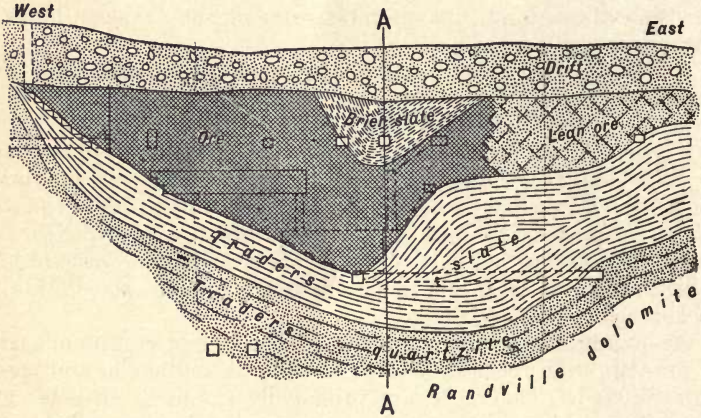


FIG. 203.—Longitudinal section of Loretto Mine, Menominee, Wisconsin.

The iron ores are of secondary origin, and mostly occur in the trough-like folds of the rocks, as shown in figs. 200 and 203.

HISTORY OF THE PRE-CAMBRIAN.

The first pages of the geological record are exceedingly fragmentary, and refer to a time so veiled in obscurity that it is almost impossible to construct a picture of the contemporary physical geography that can claim to be more than a shadowy approximation.

We have already observed that the Archæan is chiefly composed of altered igneous rocks, mostly of intermediate and basic types, with subordinate intercalated bands of sedimentaries, among which calcareous members are conspicuously absent.

Of the land surface on which these piles of Archæan igneous rocks were spread, we have no record of any kind. It may have been a portion of the primitive, wrinkled, and gnarled crust that formed when the globe first cooled down, or a surface composed of sedimentary and igneous rocks spread over the primitive crust. The subject is one that affords ample scope for controversy, and, although full of interest, is, after all, more academic than material. What we do know is that on this ancient land surface, whatever its character and origin, there was poured a stupendous accumulation of lavas mingled with piles of fragmentary ejectamenta. The distribution of these Archæan rocks would seem to warrant the belief that the regions in which these titanic outbursts took place already formed the nucleus or framework of the existing continents.

So far as we know, the Archæan rocks were not the product of a single world-wide paroxysmal outburst, but the accumulation of many eruptions, possibly separated by long intervals of comparative quiescence. During the periods of cessation from volcanic activity, the still smoking piles of lavas and ashes became subject to denudation, the detritus being deposited in the adjacent seas, where it afterwards became covered with the ejecta of later eruptions. In this way were formed the bands of conglomerate and shale intercalated among the igneous rocks.

The absence of calcareous bands has been thought by some writers to indicate that the seas of these Archæan times were devoid of lime and other dissolved salts, but of the truth of this we are in complete ignorance.

After an interval of unknown length the lavas and tuffs became invaded by enormous plutonic intrusions of acid magmas, which now constitute the granites and gneisses of the Laurentian.

This was apparently a period of general uplift during which the continents attained a great area, particularly in North America and Western Europe. The beginning of this uplift ends the first or Archæan chapter of the Earth's history, which was mainly characterised, as we have seen, by unparalleled volcanic activity.

The duration of the post-Laurentian uplift is unknown. That it was very great may be gathered from the enormous alteration, folding, and erosion suffered by the Archæan rocks before the Algonkian period began.

The Algonkian is mainly sedimentary, and comprises four great systems separated by unconformities. The systems are a record of subsidence and deposition, and the unconformities of long intervals of uplift and denudation.

The vast thickness of the Algonkian is a witness of prolonged and probably rapid denudation of land-areas long since worn down to a low relief, and covered over with later rock-formations.

The alternating subsidence and uplift, deposition, and denudation resulting in the formation of conglomerates, sandstones, shales, and limestones, now highly altered and deformed, indicate the prevalence of physical conditions in the Algonkian not unlike those of the present day. With such conditions it is not surprising to find many evidences of life; although this truth might have been postulated from the existence of the limestone bands, and the highly organised character of the succeeding Cambrian faunas which it is reasonable to suppose must have been preceded by a long line of ancestors.

CHAPTER XXII.

PALÆOZOIC ERA.

The Palæozoic formations have been subdivided on palæontological grounds into six easily recognised systems :—

6. Permian.
5. Carboniferous.
4. Devonian.
3. Silurian.
2. Ordovician.
1. Cambrian.

The Palæozoic is the lowest of the three great fossiliferous divisions of sedimentary rocks. It is characterised by the presence of the oldest known organic remains, if we except the few indistinct fossils found in the Eozoic of North America.

The flora is mainly cryptogamic, comprising gigantic ferns, club-mosses, and horse-tails, which in the upper half are associated with conifers and cycads.

The fauna is specially distinguished by its crinoids, corals, graptolites, peculiar brachiopods, ancient nautili, trilobites, and ganoid fishes. Reptiles just appear at the close, and birds are entirely absent.

The rocks are represented by sandstones, grits, conglomerates, shales, slates, and limestones, frequently tilted, folded, faulted, cleaved, and metamorphosed.

In many places they are intercalated with contemporaneous sheets of lava, and intruded by igneous dykes.

The total thickness of the formations included in the Palæozoic is estimated at 100,000 feet.

In the lower half the Palæozoic contains deposits of gold, silver, tin, and iron ; and in the upper half valuable seams of coal.

When dealing with the Eozoic, in the absence of fossils, we found it impossible to correlate the sandstones of Loch Torridon with those of Longmynd, or the Lewisian gneiss of Scotland with that of Ireland or Anglesey, and still less possible to correlate the ancient rocks of the British Isles with those of Scandinavia or Canada; but when we reach the fossiliferous Palæozoic formations, all this is changed. The contained fossils enable us to say within narrow limits of error that a certain rock in Great Britain is contemporaneous with such a one in Bohemia, India, Tasmania, or Canada. Moreover, by a careful study of the character of the fossils and of the sediments in which they are embedded, we are able to determine the physical conditions that prevailed simultaneously on the different continents with an approximate degree of certainty.

Relationship of Outcrop to Actual Extent of Formations.—When we say that a rock-formation or system "occupies," "covers," or "occurs in" a certain tract of country; or when we speak of it as being "well-developed" or "represented" in a specified locality, we refer only to the portion of the formation exposed at the surface. Obviously the portion so exposed may be only a fraction of the total area in which the formation exists, which is only another way of saying that the greater portion of the formation may lie buried beneath younger rocks.

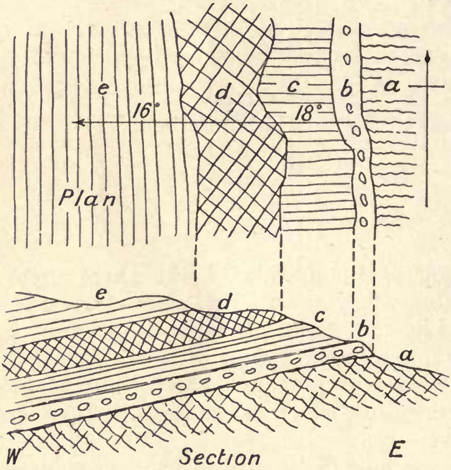


FIG. 204.—Showing relationship of outcrop to actual extent of a rock-formation.

(*a*) Archæan. (*b* and *c*) Cambrian. (*d*) Ordovician. (*e*) Silurian.

For example, we know that the surface exposures of the Carboniferous Coal-Measures of England cover but a small portion of the area actually occupied by that formation. Bore-holes have proved a great easterly extension into Kent under the overlying Oolite, Greensands, and Chalk; and coal has been discovered at Dover, 1100 feet below the sea, over 100 miles from the nearest outcrop of the Coal-Measures in England.

In this plan and section we see that the surface exposure of the Cambrian *a* amounts only to *x*, while as a matter of fact that system exists far to the westward of the outcrop below *d* and *e*; and so far as we can see it appears to be co-extensive with the Ordovician and Silurian.

The surface exposure of a rock-formation is usually the result of some accident of folding, tilting, or faulting followed by denudation. Hence a map which shows only the present exposure of a rock-formation conveys no information as to the extent of the sea-floor on which the original sediments were laid down.

CAMBRIAN SYSTEM.

The name *Cambrian* is derived from Cambria, the ancient name of Wales. It was first proposed by Sedgwick in 1833 for a certain group of fossiliferous rocks in North Wales, which subsequent research showed to be Silurian and Ordovician. The name is now confined to the oldest group of Palæozoic fossiliferous strata, and is recognised as a time-name by geologists in all countries.

Distribution.—Cambrian rocks are found in all the continents. They are typically developed in North Wales, where they attain a thickness of 12,000 feet. They are well represented in North Scotland, also in Spain, France, Belgium, Bohemia, and other parts of Central Europe, where their thickness is estimated at 10,000 feet.

In Scandinavia the Cambrian system dwindles down to a few hundred feet of shales and thin-bedded limestones, which indicate deep-water conditions of deposition. Obviously the ancient continent, near which the thicker arenaceous Cambrian rocks of Wales were laid down, existed somewhere to the westward.

The Cambrian rocks in North America occupy a wider extent of country and attain a greater thickness than in any other known part of the globe. They also present a type of sedimentation typically distinct from that of Continental Europe. In the Adirondack Mountains of New York, in East Canada, in the Appalachian Chain, stretching through Pennsylvania, Virginia, Tennessee, Georgia, and Alabama, in Central Nevada, and British Columbia, they are represented by sandstones, shales, and massive beds of limestone that are frequently dolomitic. The thickness of the system in North America varies from 2000 to 10,000 feet. Of a thickness of 7700 feet in Nevada, more than 4000 feet are beds of massive limestones; and in all the States the calcareous members are conspicuous, particularly in the upper divisions of the system.

Cambrian rocks crop out from below later accumulations in the Andes in North-West Argentina, in the Salt Range in India, in Korea, in South-East Australia, and in Tasmania. Cambrian corals have been found in South Victoria Land.

Rocks.—The rocks of the Cambrian system mainly consist of sandstones, grits, greywackes, shales, slates, and limestones. They are frequently associated with bands of quartzite, quartz-schist, phyllite, and mica-schist.

As might be expected from their great antiquity, the Cambrian rocks are much disturbed, particularly in Great Britain, where they are tilted at high angles, sharply folded and metamorphosed. In North America, Scandinavia, and Russia they lie comparatively undisturbed over considerable areas ; but in Eastern Russia they rise up in folds as they approach the Ural Mountains.

In England, France, and Belgium the Cambrian rocks are intercalated with sheets of diabase and diabase-tuff, and intruded by dykes of quartz-porphyry and diorite.

In North America the Cambrian rocks are comparatively free from contemporaneous volcanic materials, but in many of the States they are intruded by igneous dykes of later date.

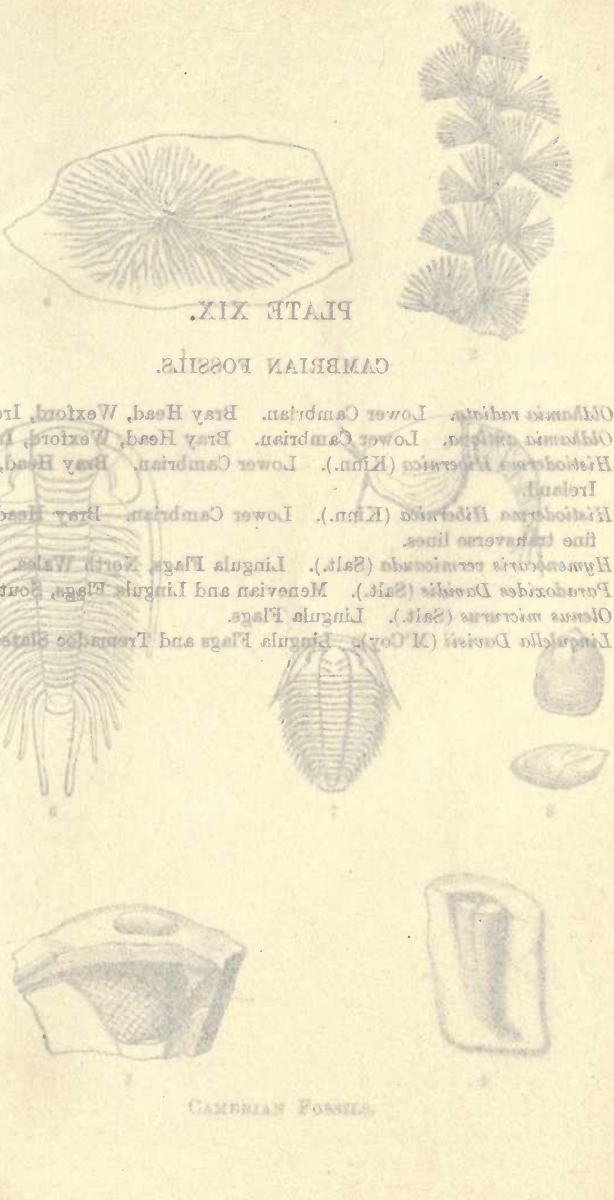
Fauna.—The fauna of the Cambrian System is remarkably rich and varied for rocks of such great antiquity. The lowest forms of life represented are radiolaria and sponges. Graptolites appear at the close, and many beautiful jelly-fish (*Medusæ*) have been described by Walcott from the Middle Cambrian of Alabama.

Corals are abundant in the limestones of North America, but comparatively rare in Europe, where the conditions of arenaceous deposition were not favourable for their existence. Hence it is that in Europe limestones are scarce, except in a limited area in North-West Scotland, where massive beds of Cambrian limestone are well developed. Crinoids and starfish are fairly common.

Annelids, which first made their appearance in the Algonkian, are known to have been numerous, as shown by the plentiful occurrence of their trails and burrows. Specimens of *Salterella* (*Serpulites*) *Maccullochi*, a tubicolous worm, are not uncommon in the Lower Cambrian of Scotland and North America.

The most distinctive of the Cambrian fossils are the Crustacea, most of which belong to the extinct trilobites. These exhibit a relatively high state of development, which would point to a long line of ancestors in pre-Cambrian times. Shrimp-like crustaceans appear for the first time in the Upper Cambrian.

Brachiopods of a peculiar type are represented by several hingeless forms, among which *Paterina labradorica* is common. Among other types are *Lingulella* and *Orthis*, which become plentiful in the next period ; and of the Mollusca we have numerous Lamellibranchs,

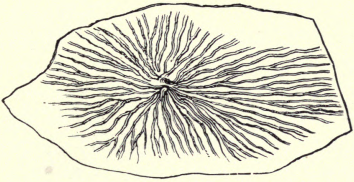


CAMBRIAN FOSSILS.

PLATE XIX.

CAMBRIAN FOSSILS.

1. *Oldhamia radiata.* Lower Cambrian. Bray Head, Wexford, Ireland.
2. *Oldhamia antiqua.* Lower Cambrian. Bray Head, Wexford, Ireland.
3. *Histioderma Hibernica* (Kinn.). Lower Cambrian. Bray Head, Wexford, Ireland.
4. *Histioderma Hibernica* (Kinn.). Lower Cambrian. Bray Head, showing fine transverse lines.
5. *Hymenocaris vermicauda* (Salt.). Lingula Flags, North Wales.
6. *Paradoxides Davidis* (Salt.). Menevian and Lingula Flags, South Wales.
7. *Olenus micrurus* (Salt.). Lingula Flags.
8. *Lingulella Davisii* (M'Coy). Lingula Flags and Tremadoc Slates.



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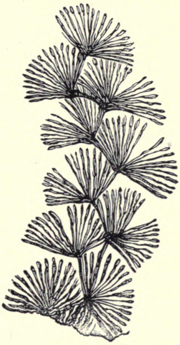

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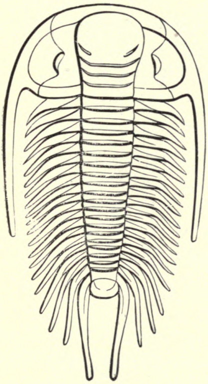

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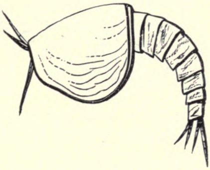

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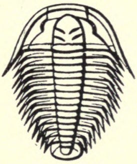

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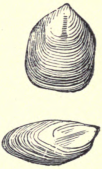

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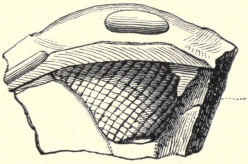

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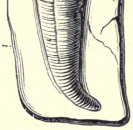

4

CAMBRIAN FOSSILS.

Gasteropods, and Cephalopods, the latter including *Orthoceras* and *Nautilus*. Among the Gasteropods we find representatives of the genera *Murchisonia* and *Pleurotomaria*.

No plant remains have yet been found in the Cambrian, though the so-called *fucoid* markings in the Middle Series (Fucoid Beds), in North-West Scotland and elsewhere have been described as the prints of sea-weeds.

Associated with worm trails there are found in the Cambrian rocks at Bray Head, Wexford, Ireland, peculiar fossil markings, called *Oldhamia*, the organic nature of which has been doubted. The two species recognised are *O. radiata* and *O. antiqua* (Plate XIX.).

Subdivision of Cambrian.—The Cambrian System has been divided into three main groups of beds, each characterised by its own assemblage of fossils. This threefold subdivision has been identified in Western Europe, North America, and Tasmania.

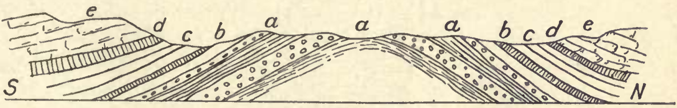

Fig. 205.—Section across Harlech Dome from Cader Idris to Snowdon.

(*a*) Harlech and Llanberis beds.
(*b*) Menevian.
(*c*) Lingula flags.
(*d*) Tremadoc.
(*e*) Ordovician.

Cambrian { Upper—*Olenus* Beds.
Middle—*Paradoxides* Beds.
Lower—*Olenellus* Beds.

The local divisions in England, as seen in the Harlech anticlinal in Western Merionethshire where the succession is complete, are as follow :—

Olenus Beds	4. Tremadoc Slates 3. Lingula Flags	Upper Cambrian.
Paradoxides Beds—	2. Menevian Series	—Middle Cambrian.
Olenellus Beds	1. Harlech and Llanberis Series	Lower Cambrian.

The three divisions recognised in North America are as under :

Upper Cambrian or *Olenus* Beds	Potsdam Sandstone.
Middle Cambrian or *Paradoxides* Beds	St John or Acadia Group.
Lower Cambrian or *Olenellus* Beds	Georgia Group.

Olenellus Beds.—These beds are everywhere considered to form the base of the Cambrian System. They contain the oldest fauna of which we have any accurate knowledge. The trilobite *Olenellus* is characteristic of this series, and hence *Olenellus Beds* and *Lower Cambrian* are synonyms.

At Harlech, in Wales, and in West England, the Lower Cambrian consists mainly of grits interbedded with bands of grey and purple slates; but in North-West Scotland the Cambrian begins with arenaceous deposits and becomes more and more calcareous and dolomitic towards the top, in this showing a curious resemblance to the Cambrian of North America.

Paradoxides Beds. — These constitute the Middle Cambrian and are distinguished by the presence of the trilobite *Paradoxides* (Plate XIX.). In North Wales they consist chiefly of dark slates; and in Canada of slates and shales, with which are correlated the limestones of Central Nevada and British Columbia. A fossil crab of a primitive type, *Sidneyia inexpectans*, occurs in the Middle Cambrian rocks of Mount Wapta, in British Columbia.

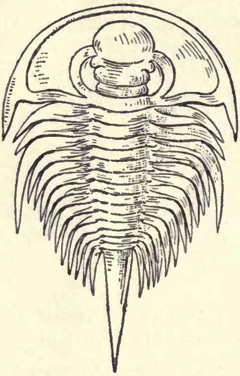

FIG. 206.—*Olenellus.*

Olenus Beds.—In North Wales, this series comprises two groups of beds, the *Lingula Flags* and the *Tremadoc Slates*, the latter forming the closing member of the Cambrian System in Britain (Plate XIX.).

The *Durness Limestone* which closes the Cambrian System in North-West Scotland contains a fauna unlike any other in the British Isles, comprising a number of species that are unknown in other British areas, but most of which have been identified in the Upper Cambrian *Calciferous Series* of the United States and Canada.

The *Calciferous Series* of North America is approximately the equivalent of the *Tremadoc Slates* of England, with which the upper and perhaps greater portion of the Durness Limestone should also be correlated.

ECONOMIC PRODUCTS.

Cambrian rocks contain veins of gold, silver, and copper, but they have nowhere proved very productive. The most valuable products obtained from this system in Great Britain are the roofing slates of the Llanberis Beds in North Wales. They alternate with conglomerates and underlie the Harlech grits. Their colour is bluish-purple; they cleave with ease and regularity, and are probably the finest roofing-slates in the world.

THE HISTORY OF DEPOSITION.

The known exposures of the Cambrian in the different continents form only a small proportion of the area actually occupied by that system, and since the area and distribution of the portions lying buried beneath the younger formations are unknown and cannot be ascertained, we are unable to reconstruct a map that will show even approximately the borders and extent of the seas in which the Cambrian sediments were laid down. Obviously, the same obscurity surrounds the area and distribution of the continents that furnished the sediments.

The fossil fauna even in the most diverse kinds of rock shows a remarkable uniformity throughout both hemispheres, from which we may reasonably draw the inference that the climatic conditions were fairly uniform throughout the globe during the Cambrian period.

The Cambrian sediments were laid down as marginal deposits around the shores of the then existing continents; and we may infer from the arenaceous character of the material, and the prevalence of worm trails and burrows, that a large proportion of the sediments were deposited in shallow seas. The red and purple colour of many of the Cambrian sandstones, the frequent ripple-marks, sun-cracks, and false-bedding might even suggest that in many instances deposition took place in shallow inland lakes, or in land-locked estuaries.

The palæontological evidence shows that the Lower Cambrian fauna of the North-West Highlands is almost identical with that of the Georgian terrain of North America, but essentially different from the Lower Cambrian fauna of the rest of Europe.

In the case of the Northern Hemisphere, it seems not improbable that the continent which provided the sediments was situated in the North Atlantic region, with long prolongations stretching far to the east and to the west, but separated from the rest of Europe by a deep sea.

Cambrian Glaciation.—In Northern Norway there is a coarse breccia-conglomerate resting on a polished and striated pavement that is believed to be glacial. The glacial beds belong to a series of sedimentary beds known as the Gaisa Beds, regarded by Reusch as equivalent to the Sparagmite formation which underlies rocks containing the *Olenellus* fauna.

A glacial boulder-rock formation containing numerous striated stones has recently been described in the upper Yang-tse Valley, in China, as lying beneath a series of rocks containing Cambrian trilobites.

Cambrian glacial deposits have been described by Howchin and David as occurring in South Australia at intervals over a distance of 150 miles; and Schwarz has reported Cambrian glacial beds in South Africa.

It would appear from these evidences of glaciation that the Eozoic rocks must, in Cambrian times, have formed high mountain chains from which glaciers descended into the sea, where they deposited their load of rocky detritus.

The general facies of the Cambrian life shows that the glaciation was not general, but confined to certain mountain chains bordering the sea-coasts in some of the continents.

CHAPTER XXIII.

ORDOVICIAN SYSTEM.

(*Lower Silurian of Murchison.*)

THE rocks now recognised as Ordovician are still included in the Lower Silurian by the Geological Survey of Great Britain, which is the position originally assigned to them by Sir Roderick Murchison, who was the first to describe and name the Silurian rocks of Wales. Sedgwick claimed them as part of his Cambrian System; and to avoid confusion Lapworth, at a later date, suggested placing them in a separate system, to which he gave the name Ordovician after the ancient British tribe Ordovices in whose territory in East Wales and Shropshire the rocks are typically developed. The name has now been adopted by geologists in many parts of the globe.

Relationships.—The Ordovician System, like the Cambrian, has been recognised in all the great continents. It rests conformably on the Cambrian and is conformably overlain by the Silurian, except in places where there is a break in the succession due to one or more of the members of the system being absent.

It will assist us to a better understanding of the relationship of the Cambrian, Ordovician, and Silurian, if we remember that these are closely related systems of conformable strata, laid down on the same sea-floor, and marginal to the same continents. In each region there was a continuance of the same physical conditions of deposition, and though the character of the sediments in many instances indicates frequent oscillations of the land, the general movement was that of subsidence. As a result of uplift in some areas, the continuance of deposition was interrupted for a time, and in such regions we have stratigraphical breaks in the succession, many of them small, others of great magnitude. Of the latter we have a good example in India, where, in the Peninsula and Salt Range, there is a great hiatus between the Cambrian and Permian, arising from a long persistent uplift after the deposition of the Cambrian.

The fauna throughout this gigantic succession of strata is closely related and stamped with the same general facies; and this is what we should expect to find in sediments laid down in the same continuous sea. In a rich and varied fauna, the dominant and characteristic organisms are trilobites and graptolites.

The threefold subdivision into Cambrian, Ordovician, and Silurian is purely empirical and based on the range of certain well-marked genera. The great thickness of the strata, and the sudden appearance, prevalence, and gradual disappearance of many generations of distinctive genera would lead to the inference that these systems covered a vast period of time of which we can make no trustworthy estimate.

Distribution.—In the British Isles, the Ordovician rocks cover a much larger area than the Cambrian. They occupy a considerable portion of Wales and the Lake District, and are also found in Shropshire, Isle of Man, and Cornwall. In Scotland they are found in the North-West Highlands, and in the Southern Uplands, where they stretch in a belt from the Firth of Clyde to the Forth. They also occur in South-East Ireland, notably in Ulster, and in Counties Galway and Mayo.

In Continental Europe, Ordovician rocks occupy large areas in Spain, North France, Scandinavia, and the Baltic provinces of Germany and Russia.

The greatest known developments of rocks of this age are found in the United States and Canada, the largest tracts occurring in the Black Hills of South Dakota, in New Mexico, Arizona, California, Utah, Nevada, Wyoming, Montana, Colorado, and further north in British Columbia.

Considerable areas of rocks that have been referred to the Ordovician occur in the Northern Himalayas, in Northern China, central South Siberia, and Arctic regions.

The Ordovician System is well represented in the Commonwealth of Australia, notably in the States of Victoria and New South Wales, and also in Western Tasmania and New Zealand. Graptolites were discovered in the South Orkney Islands by Pirie, which would support the view that the older Palæozoic formations are represented in the American quadrant of the Antarctic continent.

Rocks.—In Europe, except in the southern regions, the Ordovician consists mainly of detrital material which composes massive beds of grit, conglomerates, sandstones or quartzites, greywackes, and shales with which are associated subordinate lenses of limestone. The scarcity of calcareous rocks in the Ordovician of Europe is in marked contrast with that of North America, where limestones are conspicuously abundant. It would appear as if the conditions of deposition that prevailed in Europe and North America, in the Cambrian, were continued into the Ordovician.

To face page 327.] [PLATE XX.

SYNCLINE OF ORDOVICIAN SLATE AT WEST CASTLETON, VERMONT. (After Dale, U.S. Geol. Survey.)

To face page 327.] [PLATE XXI.

PUCKERED MICA-SCHIST FROM TACONIC RANGE.
(After Dale, U.S. Geol. Survey.)

To face page 327.]

[Plate XXII.

Schist Conglomerate from Felch Mountain District, Michigan. (U.S. Geol. Survey.)

Generally, throughout the United States and Canada, the rocks of that age are limestones, shales, and sandstones, the former always conspicuous and usually richly fossiliferous.

In the central valley of Tennessee, in Cincinnati, Alabama, and many of the neighbouring States, the Ordovician rocks lie horizontal or appear in gentle folds; but in Vermont (Plate XX.), Eastern Tennessee, West Virginia, and in the mountains of Arkansas they are tilted at high angles. In Wales and England they are tilted at various angles, and in North-West Scotland sharply folded, contorted, and involved in overthrusts.

In Wales and Shropshire the Ordovician grits, which consist mainly of resorted volcanic debris, are intercalated with thick sheets of lava and tuffs; and in the Lake District, vast piles of volcanic material dominate the system. In these areas we thus have conclusive proof of intense and prolonged volcanic activity, contemporaneous with the deposition of the fossiliferous Ordovician.

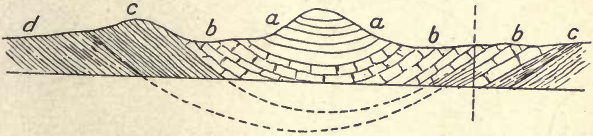

Fig. 207.—Showing structure of Taconic Mountains. (After Walcott.)

(*a*) Hudson shales. (*b*) Trenton, Chazy, and other limestones.
(*c*) Cambrian (Potsdam) micaceous shales.
(*d*) Lower Cambrian (Georgian). (*a* and *b*) = Ordovician.

In America there is little evidence of contemporaneous volcanic disturbance, the general tranquillity of the Cambrian having continued into the Silurian. The relationship of the Ordovician to the Cambrian in the Taconic Mountains is shown in the above figure. Plate XXI. shows a mica-schist.

In a general review of this period, we observe that the Ordovician, like the Cambrian, contains two distinct facies of sediments, an arenaceous and calcareous, the former typically European, the latter typically American.

Fauna.—There was a marked change in the life at the close of the Cambrian, and many genera and species abundant in that system are absent in the Ordovician, in which, however, many new forms appear for the first time.

In a rich and varied fauna graptolites and trilobites are the most important organisms, and of these the graptolites may perhaps be regarded as distinctively Ordovician. They comprise a great many genera and include two-, four-, and many-branched kinds. Among the best known are :—

Diplograptus.[1]
Tetragraptus.[2]
Cœnograptus.[3]

Corals and crinoids are numerous in the limestones and calcareous strata ; while Brachiopods are well represented by the genera *Orthis*, *Strophomena*, and *Leptæna*, which occur in the arenaceous facies of sediments, together with many Lamellibranchs and Gasteropods. Of Cephalopods we still have the persistent *Orthoceras*,[4] which first appeared in the Cambrian (Plate XXIII.).

The trilobites attain their maximum development in this period, more than half of all the known genera being peculiarly Ordovician. A few, like *Agnostus* and *Calymene*, survived from the Cambrian, while the others appear for the first time. In the Silurian they fall to half the number, and in the succeeding formations dwindle rapidly, until they finally disappear at the close of the Palæozoic.

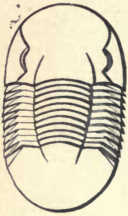

FIG. 208.
Illænus.

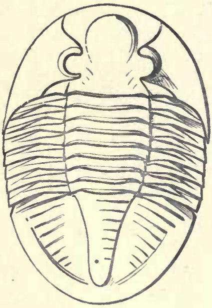

FIG. 209.
Asaphus.

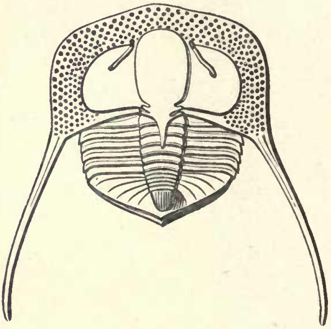

FIG. 210.—*Trinucleus.*

Among the prominent Ordovician trilobites we find *Agnostus*, *Ogygia*, *Asaphus*, *Trinucleus*, and *Illænus* (Plate XXIV.).

The remains of fish-like organisms, the earliest known vertebrates, are found abundantly in the Ordovician of Colorado.

No fossil remains of land plants are known in this period, but at Olonetz, in Finland, in a series of sandstones and dolomites ascribed to this or even an older system, there is a seam of anthracite,

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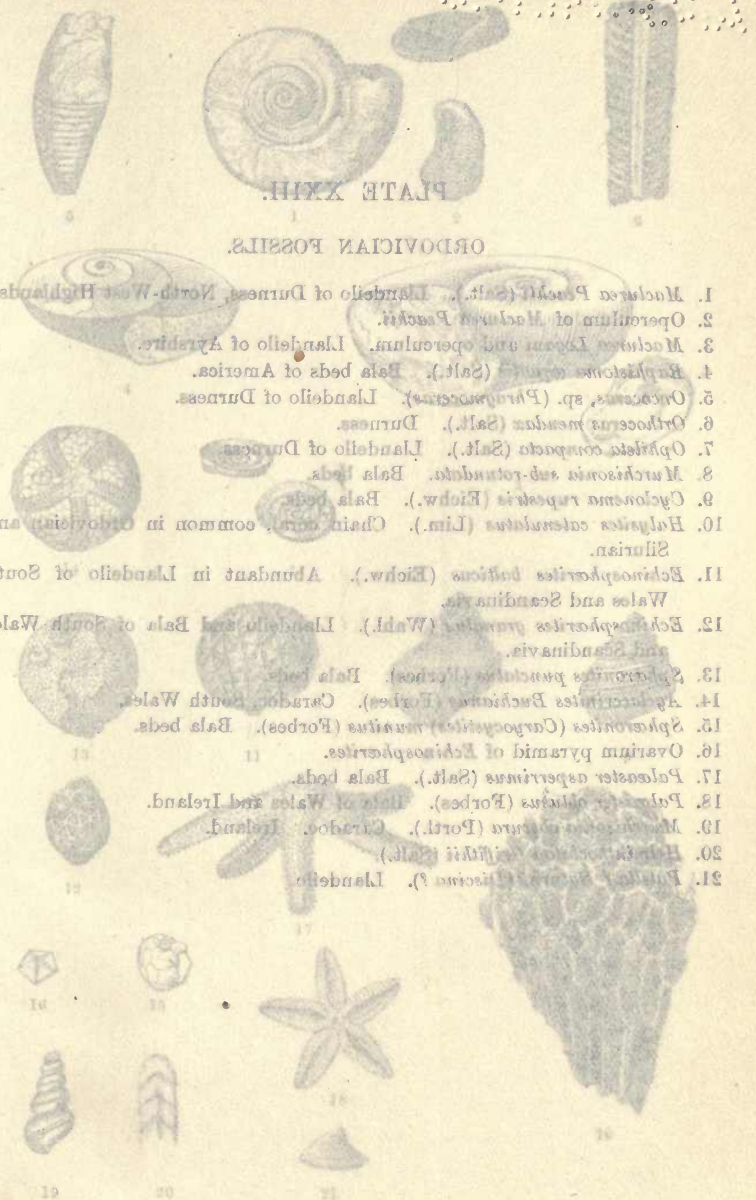
[1] Gr. *diplous* = double, and *grapho* = I write (*i.e.* pen).
[2] Gr. *tetra* = four, and *grapho*.
[3] Gr. *koinos* = kindred, and *grapho*.
[4] Gr. *orthos* = straight, and *keras* = a horn.



Ordovician Fossils.

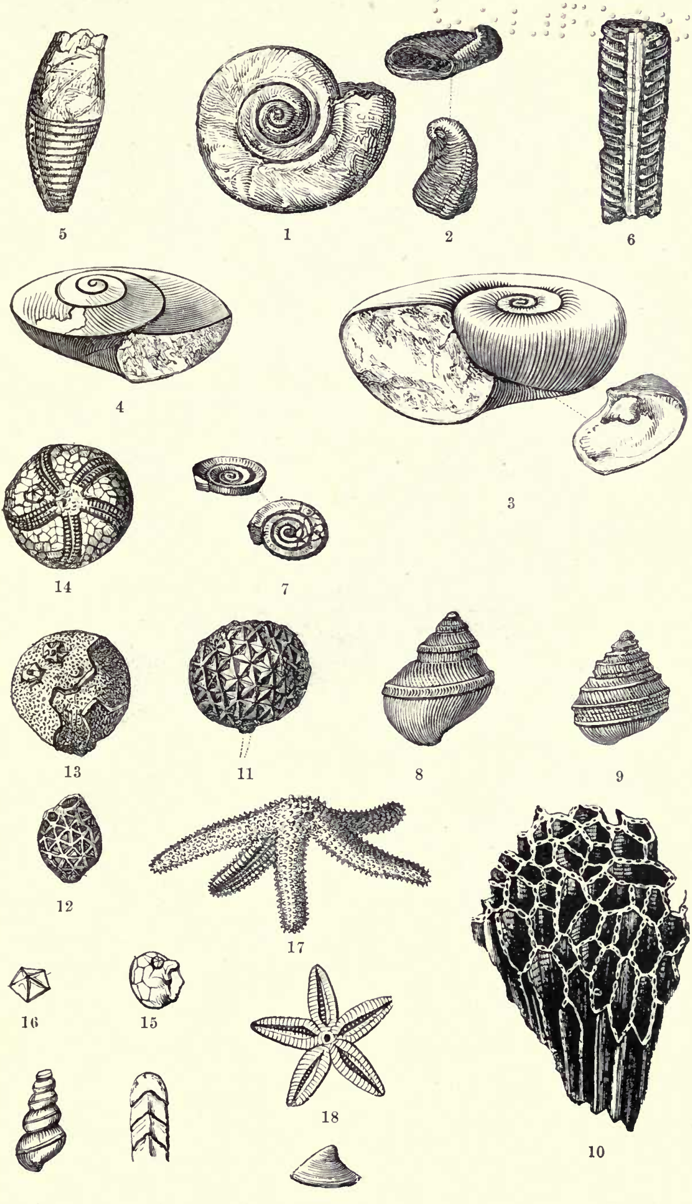
PLATE XXIII.

ORDOVICIAN FOSSILS.

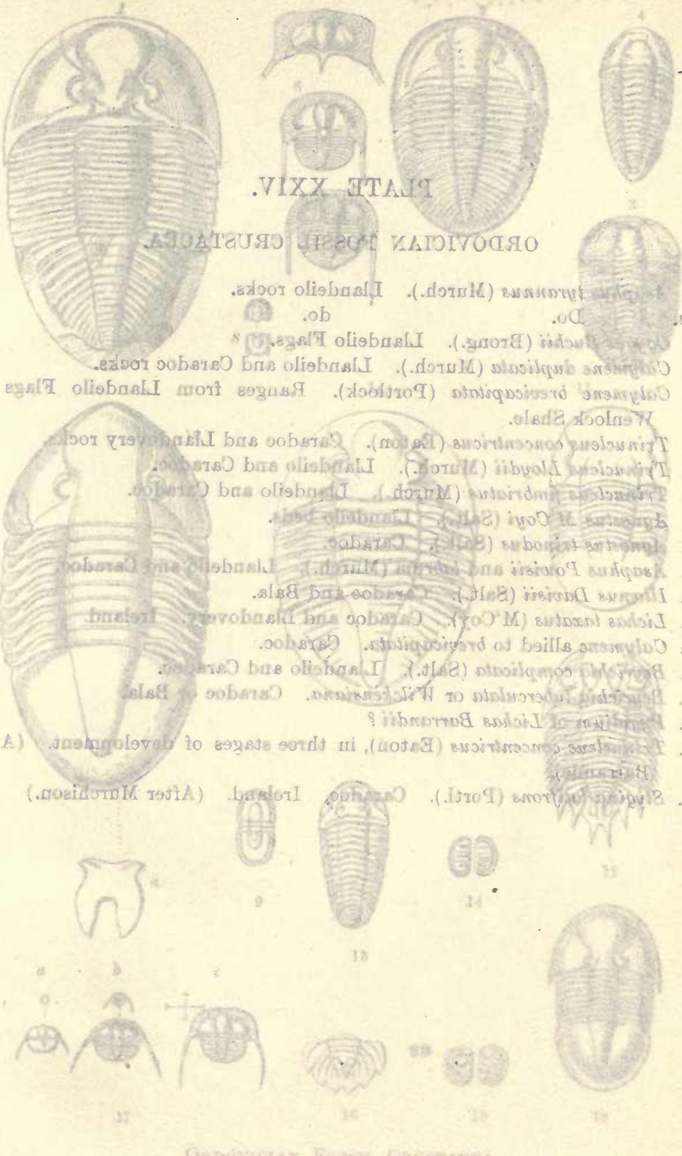
1. *Maclurea Peachii* (Salt.). Llandeilo of Durness, North-West Highlands.
2. Operculum of *Maclurea Peachii.*
3. *Maclurea Logani* and operculum. Llandeilo of Ayrshire.
4. *Raphistoma æqualis* (Salt.). Bala beds of America.
5. *Oncoceras*, sp. (*Phragmoceras*). Llandeilo of Durness.
6. *Orthoceras mendax* (Salt.). Durness.
7. *Ophileta compacta* (Salt.). Llandeilo of Durness.
8. *Murchisonia sub-rotundata.* Bala beds.
9. *Cyclonema rupestris* (Eichw.). Bala beds.
10. *Halysites catenulatus* (Lim.). Chain coral, common in Ordovician and Silurian.
11. *Echinosphærites balticus* (Eichw.). Abundant in Llandeilo of South Wales and Scandinavia.
12. *Echinosphærites granatus* (Wahl.). Llandeilo and Bala of South Wales and Scandinavia.
13. *Sphæronites punctatus* (Forbes). Bala beds.
14. *Agelaccrinites Buchianus* (Forbes). Caradoc, South Wales.
15. *Sphæronites* (*Caryocystites*) *munitus* (Forbes). Bala beds.
16. Ovarium pyramid of *Echinosphærites.*
17. *Palæaster asperrimus* (Salt.). Bala beds.
18. *Palæaster obtusus* (Forbes). Bala of Wales and Ireland.
19. *Murchisonia obscura* (Portl.). Caradoc. Ireland.
20. *Helminthochiton Griffithii* (Salt.).
21. *Patella ? Saturni* (*Discina ?*). Llandeilo.

To face page 328.]

[Plate XXIII.



Ordovician Fossils.

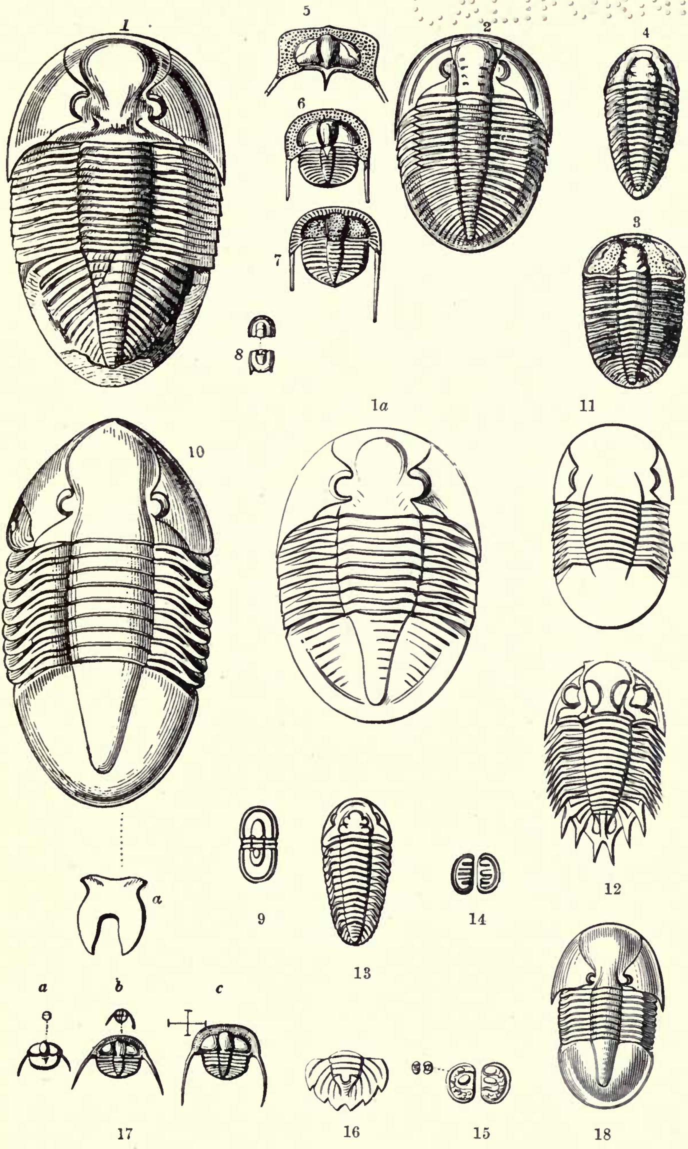


Ordovician Fossil Crustacea.

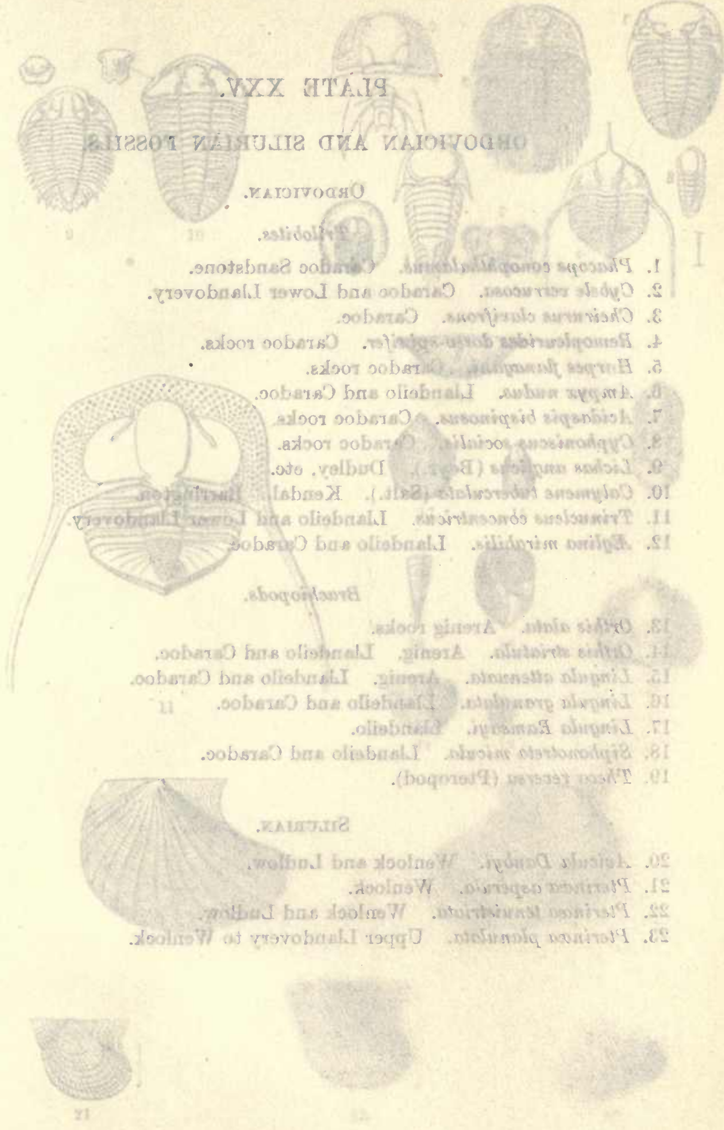
PLATE XXIV.

ORDOVICIAN FOSSIL CRUSTACEA.

1. *Asaphus tyrannus* (Murch.). Llandeilo rocks.
1*a*. Do. do.
2. *Ogygia Buchii* (Brong.). Llandeilo Flags.
3. *Calymene duplicata* (Murch.). Llandeilo and Caradoc rocks.
4. *Calymene brevicapitata* (Portlock). Ranges from Llandeilo Flags to Wenlock Shale.
5. *Trinucleus concentricus* (Eaton). Caradoc and Llandovery rocks.
6. *Trinucleus Lloydii* (Murch.). Llandeilo and Caradoc.
7. *Trinucleus fimbriatus* (Murch.). Llandeilo and Caradoc.
8. *Agnostus M'Coyi* (Salt.). Llandeilo beds.
9. *Agnostus trinodus* (Salt.). Caradoc.
10. *Asaphus Powisii* and *labrum* (Murch.). Llandeilo and Caradoc.
11. *Illœnus Davisii* (Salt.). Caradoc and Bala.
12. *Lichas taxatus* (M'Coy). Caradoc and Llandovery. Ireland.
13. *Calymene* allied to *brevicapitata*. Caradoc.
14. *Beyrichia complicata* (Salt.). Llandeilo and Caradoc.
15. *Beyrichia tuberculata* or *Wilckensiana*. Caradoc or Bala.
16. *Pygidium* of *Lichas Barrandii ?*
17. *Trinucleus concentricus* (Eaton), in three stages of development. (After Barrande).
18. *Stygina latifrons* (Portl.). Caradoc. Ireland. (After Murchison.)



Ordovician Fossil Crustacea.



ORDOVICIAN AND SILURIAN FOSSILS.

PLATE XXV.

ORDOVICIAN AND SILURIAN FOSSILS.

ORDOVICIAN.

Trilobites.

1. *Phacops conophthalamus.* Caradoc Sandstone.
2. *Cybele verrucosa.* Caradoc and Lower Llandovery.
3. *Cheirurus clavifrons.* Caradoc.
4. *Remopleurides dorso-spinifer.* Caradoc rocks.
5. *Harpes flanagani.* Caradoc rocks.
6. *Ampyx nudus.* Llandeilo and Caradoc.
7. *Acidaspis bispinosus.* Caradoc rocks.
8. *Cyphoniscus socialis.* Caradoc rocks.
9. *Lichas anglicus* (Beyr.). Dudley, etc.
10. *Calymene tuberculata* (Salt.). Kendal. Barrington.
11. *Trinucleus concentricus.* Llandeilo and Lower Llandovery.
12. *Æglina mirabilis.* Llandeilo and Caradoc.

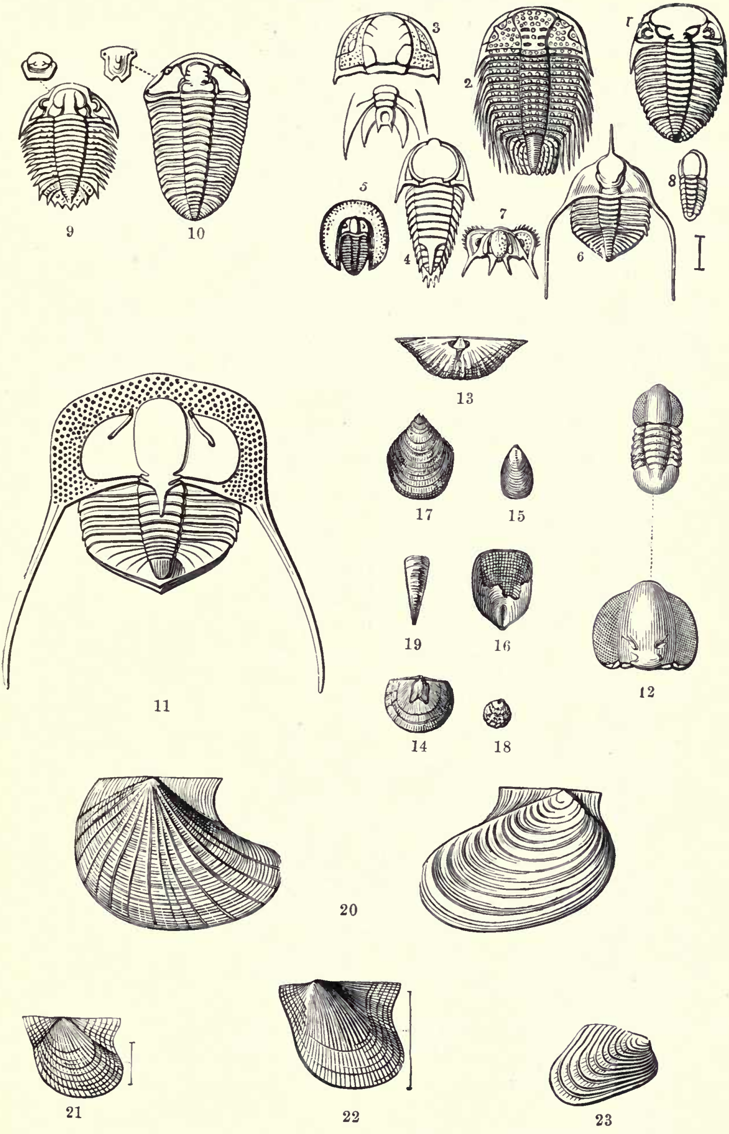
Brachiopods.

13. *Orthis alata.* Arenig rocks.
14. *Orthis striatula.* Arenig. Llandeilo and Caradoc.
15. *Lingula attenuata.* Arenig. Llandeilo and Caradoc.
16. *Lingula granulata.* Llandeilo and Caradoc.
17. *Lingula Ramsayi.* Llandeilo.
18. *Siphonotreta micula.* Llandeilo and Caradoc.
19. *Theca reversa* (Pteropod).

SILURIAN.

20. *Avicula Danbyi.* Wenlock and Ludlow.
21. *Pterinœa asperula.* Wenlock.
22. *Pterinœa tenuistriata.* Wenlock and Ludlow.
23. *Pterinœa planulata.* Upper Llandovery to Wenlock.

[PLATE XXV.



ORDOVICIAN AND SILURIAN FOSSILS.

the presence of which would appear to be evidence of the existence of peat-bogs even in these remote times.

Subdivision.—The typical subdivision of the Ordovician as seen in Shropshire is as follows, the oldest being at the bottom :—

Ordovician
3. Caradoc or Bala Beds—Grits and shales with their bands of limestone (4000 feet).
2. Llandeilo Beds—Black flags, shales, and limestones (3000 feet).
1. Arenig Beds—Black flags, grits, or quartzite (3000 feet).

With these beds there are associated great intercalated masses of lavas, tuffs, and agglomerates.

In the Lake District, where the total thickness is 20,000 feet, more than half of which is volcanic material, the succession is as given below :—

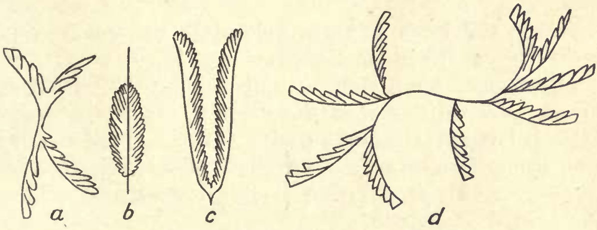


FIG. 211.—Ordovician graptolites.
(*a*) *Tetragraptus.* (*c*) *Didymograptus Murchisoni.*
(*b*) *Diplograptus.* (*d*) *Cœnograptus.*

3. Bala Group { Ashgill Beds, Coniston Limestone, Dufton Shales } 3000 feet.
2. Llandeilo Group—Borrowdale Volcanic Series (10,000 feet).
1. Arenig Group —Skiddaw Slates, upper part (7000 feet).

The Ordovician of England contains a great diversity of deposits, some containing shelly fossils, others graptolites. This has led to the construction of two parallel classifications, one for the shelly facies distinguished by characteristic trilobites, the other for the graptolitic facies, distinguished by dominant graptolites.

	Trilobites.		Graptolites.
Ashgillian	*Trinucleus seticornis.*	(Plate XXV.)	*Dicellograptus anceps.* *Diplograptus truncatus.*
	Cybele verrucosa.	,,	
	Cheirurus juvenis.	,,	

	Trilobites.	Graptolites.
Caradocian	*Trinucleus concentricus.* *Phacops apiculatus.* *Asaphus Powisi.*	*Dicranograptus Clingani.* *Pleurograptus.* *Amphigraptus.*
Llandeilian	*Trinucleus favus.* *Asaphus tyrannus.* *Ogygia Buchi.*	*Cœnograptus.* *Didymograptus Murchisoni.*
Skiddavian or Arenigian	*Trinucleus Gibbsi.* *Placoparia.* *Æglina binodosa.* *Ogygia Selwyni.*	*Phyllograptus.* *Tetragraptus.* *Didymograptus* — open-branching forms, as *D. bifidus.*

The first two comprise the Upper Ordovician = Caradoc or Bala Group.

Usually the trilobites and graptolites do not occur together in the same beds, except in the Skiddavian.

Graptolite zones were first established in 1879 by Lapworth, whose researches showed that the vertical range of the species of graptolites is comparatively limited. He recognised twenty zones, one in the Upper Cambrian, eight in the Lower Silurian (Ordovician), and eleven in the Upper Silurian. In recent years the list of zones has been greatly extended.

The best recognised subdivisions in North America, where the calcareous facies of sediments predominates, are as follow :—

Cincinnatian or Upper Ordovician	Richmond Beds. Lorraine Beds. Utica Beds.
Mohawkian or Middle Ordovician	Trenton Limestone. Black River Limestone. Lowville Limestone.
Canadian or Lower Ordovician	Chazy Limestone. Beckmantown Limestone.

These three divisions exhibit an approximate parallelism with the Bala, Llandeilo, and Arenig of Great Britain.

Ordovician rocks are well developed in South-East Australia, in the States of Victoria and New South Wales. In Victoria, where they are best known, they consist of alternating bands of slates, shales, greywackes, and quartzites that are usually tilted at high angles. Calcareous rocks are absent or but feebly represented. Fossils are abundant, and of these many European species of graptolites have been recognised. The divisions suggested by Hall for the Ordovician of Victoria are as follow :—

Upper Ordovician—4. Darriwell Series.
Lower Ordovician { 3. Castlemain Series.
2. Bendigo Series.
1. Lancefield Series.

The total thickness of these rocks amounts to many thousand feet.

Arenig Group (*Lower Ordovician*).—This group of rocks derives its name from the Arenig Mountains in North Wales. It consists of dark slates, shales, flags, and sandstones intercalated in the Shropshire area with a considerable quantity of volcanic debris. Many of the highest mountains in Wales, such as Cader Idris, Arenig, Arans, and Berwyns, are composed of these intercalated masses of lava and tuffs.

The most abundant fossils in this group are graptolites, although trilobites are also common. The characteristic graptolites are *Tetragraptus serra*, *Didymograptus extensus*, and *D. bifidus*.

In the North of England, where only the upper part of the Skiddaw slates appears to be Ordovician, there is little or no evidence of volcanic activity during Arenig times.

Llandeilo Group (*Middle Ordovician*).—This group consists of dark-coloured flagstones, sandstones, and shales; all sometimes more or less calcareous. It also contains a bed of limestone with a rich assemblage of fossils, including many trilobites and shells. The graptolites are abundant and best preserved in the shales.

In Shropshire the Llandeilo beds contain many evidences of contemporaneous volcanic activity, and in the Lake District the Skiddaw slates are followed by an enormous accumulation of basic, andesitic, and rhyolitic lavas, tuffs, and agglomerates, to which the name *Borrowdale Series* has been applied. The estimated thickness of this volcanic pile is 10,000 feet.

The alternating hard and soft bands of volcanic rock have given rise under the influence of denudation to the great diversity of surface features which has made the Lake District one of the most attractive and picturesque regions in Britain. Conspicuous among the mountains composed of the volcanic rocks of the Borrowdale series are Scawfell and Helvellyn.

Among the characteristic graptolites of the Llandeilo Group is *Didymograptus Murchisoni*, which is abundant in the lower beds, and having only a limited range, possesses a zonal value. Trilobites are numerous and include *Asaphus tyrannus* (Plate XXIV. fig. 1) in the lower, and *Ogygia Buchii* (Plate XXIV. fig. 2) in the upper portion.

Bala Group (*Upper Ordovician*).—This group, which closes the Ordovician System, is named after the town of Bala, where two bands of fossiliferous limestone are well exposed. The Caradoc

Sandstone in Shropshire is also of the same age, hence the dual name *Bala* or *Caradoc* frequently applied to this group of beds.

The Bala Limestone of Wales is believed to be the horizontal equivalent of the Coniston Limestone of the Lake District.

The most abundant genera of Bala graptolites are *Diplograptus* and *Climacograptus.*

The Bala period was characterised by great volcanic activity, and thick masses of lava and ashes were intercalated with the marine sediments. In many cases the volcanic ash-beds are fossiliferous.

Lying below the *Bala Ash* there is a vast pile of rhyolitic lavas and tuffs which culminates in the peaks of Snowdon, Glyders, and Y-Tryfaen.

Conditions of Ordovician Deposition.—The physical geography of this period was a continuance of that of the Cambrian; and deposition appears to have taken place in the Northern Hemisphere around the southern shores of a great North Atlantic continent. Intense local volcanic activity prevailed in the Lake District and in Shropshire in England; but elsewhere there appears to have been little or no disturbance. The character of the sediments and contained fauna afford some evidence of minor oscillations of the land, but the general movement was that of subsidence.

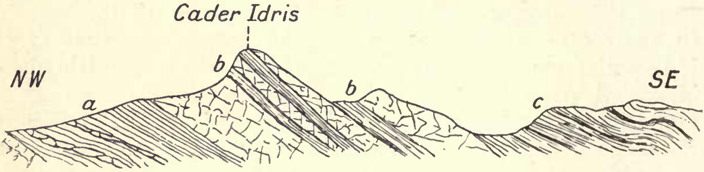


Fig. 212.—Section across Cader Idris. (After Murchison.)

(*a*) Lingula flags and Tremadoc slates with bands of porphyry.
(*b*) Massive porphyrites and greenstones, alternating with (*c*).
(*c*) Arenig and Llandeilo beds.
(*a* and *b*) = Upper Cambrian. (*c*) = Ordovician.

Economic Products.—The economic importance of the Ordovician is considerable. In the United States the Trenton formation constitutes one of the most productive oil and gas horizons. In Central Tennessee the Ordovician limestones contain large deposits of rock-phosphate; and in Wisconsin and the adjoining States of Iowa and Illinois, valuable ores of lead and zinc occur as replacement deposits in cavities in the limestones of this period.

The mineral-bearing value of the Ordovician rocks in Europe is unimportant. In Australia they contain the celebrated gold-bearing *saddle-reefs* of Bendigo, which have already added about £75,000,000 to the wealth yielded by the State of Victoria.

CHAPTER XXIV.

SILURIAN SYSTEM.

(*Upper Silurian, Murchison and British Geological Survey.*)

SILURIAN rocks are typically developed in Shropshire, and in Central and South Wales, the country of the ancient British tribe *Silures*. They were first described by Sir Roderick Murchison, whose "Siluria" embraced what is now known as the Ordovician and Silurian systems.

Distribution.—Besides occurring in Shropshire and Wales, Silurian rocks occupy nearly the whole of the southern portion of the Lake District; while further north they are extensively developed in the Southern Uplands of Scotland, where they stretch as a wide belt from the Mull of Galloway on the south-west coast to St Abb's Head, near the Firth of Forth.

The continuation of this belt is found across the Irish Sea in West Ireland where it occupies the greater portion of County Down, whence it extends in a south-west direction through the adjoining counties until it eventually disappears beneath the Carboniferous Limestone. There is a patch of Silurians in County Dublin, and many isolated outcrops occur in the provinces of Connaught and Munster.

The Silurian system occupies a large area in North-East France, also in Scandinavia, Finland, and Russia, where it forms a wide belt that runs parallel with the Ordovician as far east as the Ural Mountains. It covers large tracts in Western China, Northern India, Burma, New South Wales, Victoria, Tasmania, New Zealand, Brazil, Peru, and Bolivia.

In North America Silurian rocks are typically developed in the Appalachian Mountains of New York, and in the States of Pennsylvania, Ohio, Michigan, Indiana, and Illinois, all bordering the Lake Country. West of the Mississippi, they extend into Missouri and Arkansas. North of the Lakes, the Silurians extend into Ontario and adjoining States of Canada; and a considerable development is found west of Hudson's Bay and in Greenland.

Rocks.—The rocks of this system are almost everywhere sandstones, shales, and limestones. The latter are sometimes dolomitic.

In the European and Asiatic regions the Silurian rocks are more or less arenaceous and calcareous, and show a close approach to the calcareous facies which characterises the lower Palæozoic rocks of North America. As a consequence of this new phase of Silurian deposition in Europe, the two facies of life — the shelly and graptolitic — so characteristic of the British Ordovician, is not well marked, and in the higher beds is hardly recognisable.

Silurian rocks in all parts of the globe are remarkably free from contemporaneous volcanic material, from which it would appear that a period of general tranquillity followed the close of the Ordovician.

Fauna.—The general facies of the fauna is similar to that of the closely related Ordovician System; and trilobites and graptolites still remain the dominant organisms.

The distinctive Ordovician genera of graptolites are now mostly replaced by the uniserial forms belonging to the *Monograptidæ*.

Corals are still abundant, but the coral-like bryozoans show a marked decline. Crinoids now reached the summit of their development, being so numerous as to form almost the whole of some massive beds of limestone.

Sea-urchins and starfish are still well represented, especially in the higher beds of the system.

Brachiopods are particularly abundant, and include some new genera, among which we find *Pentamerus*, *Stricklandia*, and *Dayia*. *Spirifers*, a distinctive type of straight-hinged Brachiopod, first appear in the Silurian, but they attain their greatest development in the Devonian and Carboniferous.

The molluscs are still represented by Lamellibranchs, Gasteropods, and Cephalopods; but it should be noted that the large straight *Orthoceras*, which is the sole representative of the Cephalopods in the Cambrian, is now less abundant though still common; while the curved and coiled forms which first appeared in the Ordovician are plentiful, and represented by a great many genera and species.

The trilobites are still represented by *Illænus*, *Calymene*, *Phacops*, and *Homalonotus*; but the new genera that appear are insufficient to balance the losses due to the disappearance of many Ordovician types; and generally throughout this system there is a sensible decline of the trilobites.

The decline of these ancient crustaceans is more than compensated by the advent in the late Silurian of a group of remarkable crustaceans mainly distinguished for their abnormal size. The most characteristic of these are the gigantic *Pterygotus* and great *Eurypterus*. The former attained a length of six feet, while examples of the latter from one foot to a foot and a half are common.

The fish remains found so abundantly in the *Bone Bed* in the Ludlow Series are the earliest British vertebrates.

Fossil insects are plentiful and include scorpions; but of the land flora and fauna which clothed and peopled the Silurian continents singularly little is known. Many of the Ordovician and Silurian shales are black with diffused anthracite, which probably represents the altered form of land and aquatic plants.

Relationships.—The Silurian is normally conformable to the Ordovician with which it is usually co-existent; although in some regions in Europe and North America it is absent where the latter is present, and in Northern Canada is present where the Ordovician is missing.

In regions where uplift took place after the close of the Ordovician, the Silurian is missing; and, conversely, where the submergence of some of the continental tracts that had remained dry land since pre-Cambrian times took place, Silurian sediments were deposited in areas in which no Ordovician or Cambrian rock existed.

In many places the Silurian rocks overlap the Ordovician, and rest unconformably on older rocks. This overlap is *landward*, and arises from the subsidence of low flat shelving coastal lands that permitted a rapid advance of the sea.

In the British Isles the Silurian and the related Ordovician beds are usually tilted and folded, and in the Southern Uplands of Scotland are compressed into numerous isoclinal folds.

In Northern Europe and North America the Silurian rocks are comparatively undisturbed.

Subdivision.—The Silurian system on the borders of Wales, where Murchison first worked out the succession, begins with conglomerates and sandstones—that is with beach deposits—and these are followed by the deeper water shales and limestones which alternate with one another, the shales being for the most part graptolitic and the limestones shelly.

Towards the top of the system the rocks again become sandy, and as we ascend, the sandstones become redder and brighter, and finally pass into the overlying *Old Red Sandstone* of Devonian age.

In the prevailing life of these three groups of beds we have in Britain the basis of a threefold division of the Silurian System, which, omitting the details, is as follows:—

Clunian or Downtonian	Passage Beds	Ledbury Shales. Downton Sandstone.
	3. Ludlow Series (1800 feet)	Upper Ludlow. Aymestry Limestone. Lower Ludlow Shale.
Salopian	2. Wenlock Series (2000 feet)	Wenlock Limestone. Wenlock Shale. Woolhope Limestone.
Valentian	1. Llandovery Series (1000 to 3000 feet)	Tarannon Shale. Upper Llandovery. Lower Llandovery.

Nowhere are the Silurian rocks so well developed as at Woolhope, near Hereford, where they mantle round the central dome composed of the Upper Llandovery Sandstones, as shown in fig. 213.

Llandovery Series.—The rocks of this series consist mainly of sandstones and conglomerates, and like all shore-deposits vary greatly in character and thickness. The numerous shells they sometimes contain render them calcareous.

In the Lake District and Moffat in Dumfriesshire, the Llandovery is represented by graptolitic shales, but at Girvan, in Ayrshire, we have the normal conglomerates, sandstones, and limestones.

In some places there is a break at the base of the series, in others, in the middle. Frequently the higher beds overlap the lower, and rest directly on the Ordovician. The breaks arise from minor uplifts, and the overlap from subsidence of a sea-littoral of low relief.

Among the characteristic Brachiopods of the Llandovery beds and the genera *Pentamerus*, *Stricklandia*, and *Meristella*. *Orthis*, *Atrypa*, and *Strophomena* are also present. *Pentamerus undatus* is perhaps the most prevalent species in the lower division, and *P. oblongus* in the upper. Trilobites are also found in these beds.

The Tarannon beds which form the upper member of the Llandovery series consist of soft green and purple slates. They contain few fossils.

Wenlock Series.—The two bands of limestone in this series are merely local intercalations in the Wenlock Shales. They contain an abundance of well-preserved fossils.

The Wenlock Shales contain several species of graptolites, notably the uniserial *Monograptus*[1] *priodon*, which is a useful zonal form, and *Cyrthograptus*.

Among the most numerous fossils in the calcareous bands are the corals *Halysites*, *Heliolites*, and *Favosites* (Plate XXVI.). Other fossils are the trilobites *Calymene*, *Phacops*, and *Illœnus*; the

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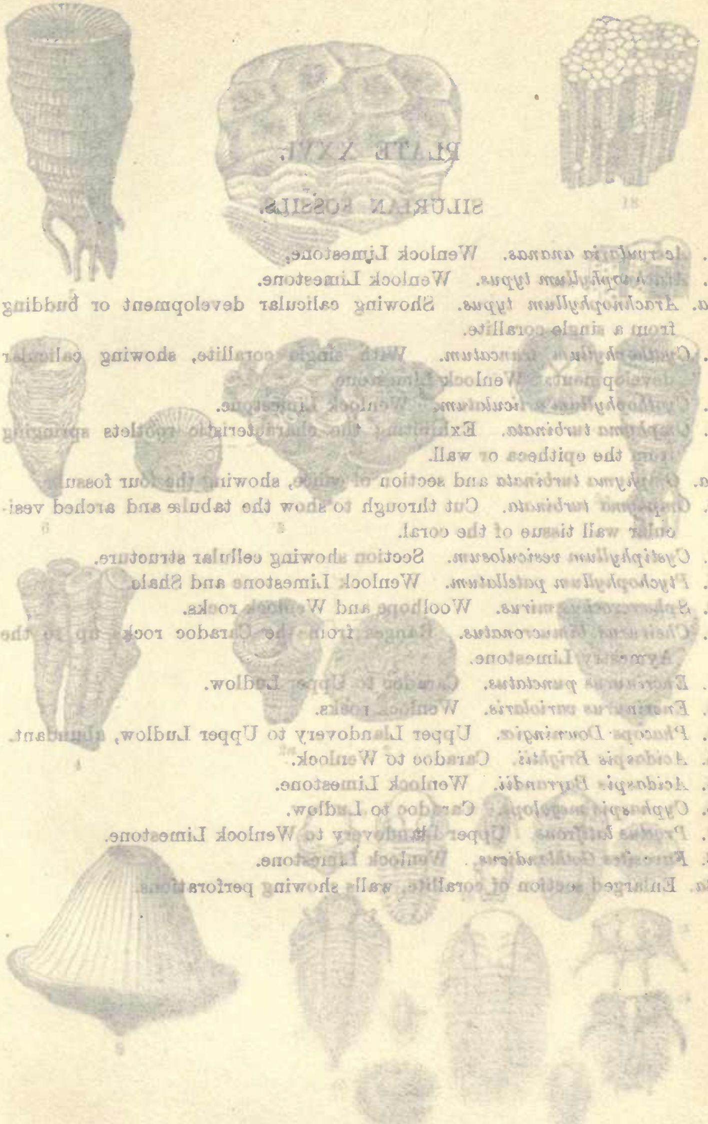
[1] Gr. *monos* = single, and *grapho* = I write.



SILURIAN FOSSILS.

PLATE XXVI.

SILURIAN FOSSILS.

1. *Acervularia ananas.* Wenlock Limestone.
2. *Arachnophyllum typus.* Wenlock Limestone.

2*a*. *Arachnophyllum typus.* Showing calicular development or budding from a single corallite.

3. *Cyathophyllum truncatum.* With single corallite, showing calicular development. Wenlock Limestone.
4. *Cyathophyllum articulatum.* Wenlock Limestone.
5. *Omphyma turbinata.* Exhibiting the characteristic rootlets springing from the epitheca or wall.

5*a*. *Omphyma turbinata* and section of calice, showing the four fossulæ.

6. *Omphyma turbinata.* Cut through to show the tabulæ and arched vesicular wall tissue of the coral.
7. *Cystiphyllum vesiculosum.* Section showing cellular structure.
8. *Ptychophyllum patellatum.* Wenlock Limestone and Shale.
9. *Sphærexochus mirus.* Woolhope and Wenlock rocks.
10. *Cheirurus bimucronatus.* Ranges from the Caradoc rocks up to the Aymestry Limestone.
11. *Encrinurus punctatus.* Caradoc to Upper Ludlow.
12. *Encrinurus variolaris.* Wenlock rocks.
13. *Phacops Downingiæ.* Upper Llandovery to Upper Ludlow, abundant.
14. *Acidaspis Brightii.* Caradoc to Wenlock.
15. *Acidaspis Barrandii.* Wenlock Limestone.
16. *Cyphaspis megalops.* Caradoc to Ludlow.
17. *Proetus latifrons.* Upper Llandovery to Wenlock Limestone.
18. *Favosites Gothlandicus.* Wenlock Limestone.

18*a*. Enlarged section of corallite, walls showing perforations.

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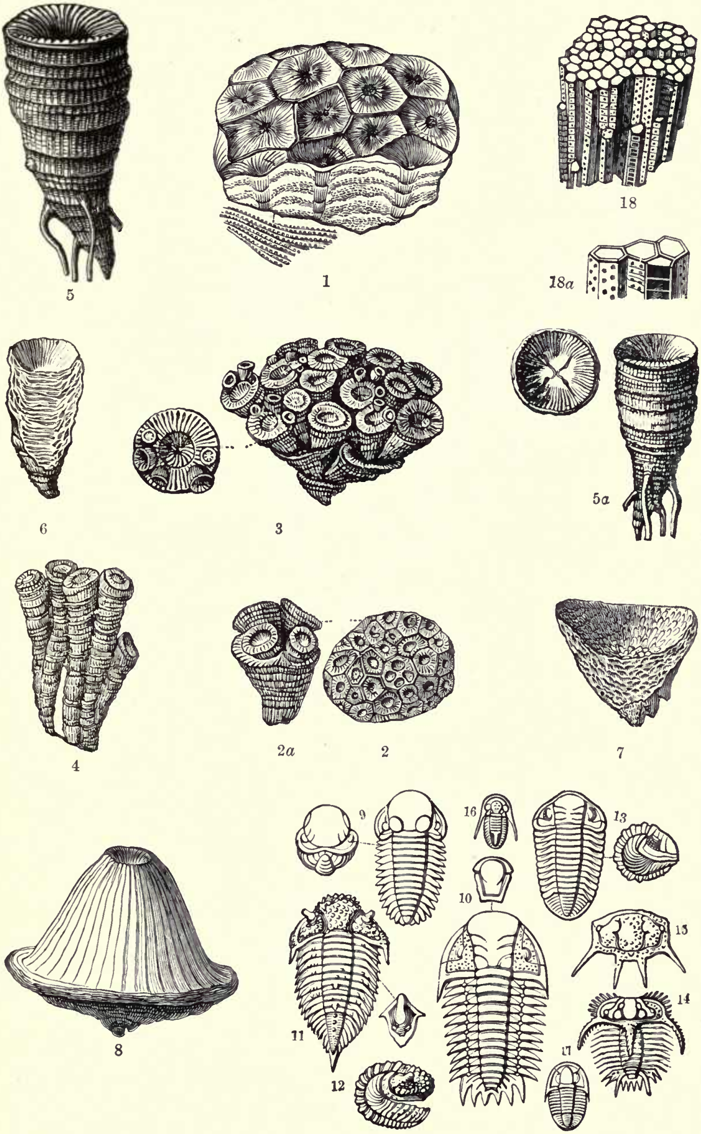
[PLATE XXVI.



SILURIAN FOSSILS

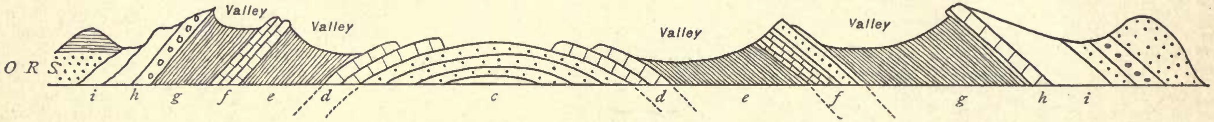


FIG. 213.—Section across Woolhope anticline.

Ludlow. Wenlock. Woolhope Beds. Upper Llandovery. Woolhope Beds. Wenlock. Ludlow. O.R.S.

(*c*) Upper Llandovery sandstones.	(*g*) Lower Ludlow.
(*d*) Woolhope beds.	(*h*) Aymestry limestone.
(*e*) Wenlock shales.	(*i*) Upper Ludlow.
(*f*) Wenlock limestone.	(O.R.S.) Old Red Sandstone.

Brachiopods *Atrypa* and *Orthis*; and the Cephalopod *Orthoceras primævum.*

Ludlow Series.—The Lower Ludlow shaly mudstones of this series are more sandy than the underlying Wenlock Shales, and in places contain a graptolitic fauna; in others a shelly. Near Ludlow they contain a number of graptolites, including the characteristic *Monograptus colonus* of zonal value, and *Cyrthograptus.*

The Aymestry Limestone also contains many fossils, including the Brachiopods *Pentamerus* and *Dayia.*

The Upper Ludlow beds are soft grey shales that alternate with thin bands of limestone. Towards the top, where they are sandy, they contain the well-known *Bone Bed*, which is a thin bed full of the bones and spines of fishes together with fragments of the great Eurypterids.

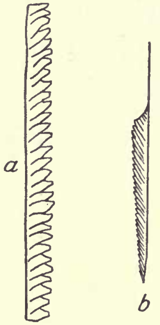


FIG. 214.—Showing uniserial graptolites.
(*a*) *Monograptus priodon* (Brown). (*b*) *Monograptus colonus* (Barr).

The principal genera of Eurypterida are *Eurypterus*,[1] *Pterygotus*,[2] and *Slimonia*. *Pterygotus anglicus* is the largest known crustacean, and is the *seraphim* of quarrymen.

North American Divisions.—The three main divisions of the Silurian recognised in North America are as follow:—

Silurian
3. Salina (or Cayugan) Series.
2. Niagaran Series.
1. Oswegan Series.

The rocks are mainly conglomerates and grits at the base followed by sandstones, shales, limestones, and dolomites. The fauna follows the same general succession as in Western Europe, but

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[1] Gr. *eurys* = broad, and *pteron* = a fin.
[2] Gr. *pteryx* = a wing, and *otos* = an ear.

an exact parallelism cannot be established between the three main British and North American divisions.

Conditions of Deposition.—At the base of the Salina Series in New York there are lenticular beds of rock-salt varying from 40 to 80 feet thick. These cover an area of nearly 10,000 square miles, and would tend to show that after the Niagaran period the general uplift, which seems to have affected the whole of the northern continents after the mid-Silurian, enclosed great shallow lagoons or land-locked seas. The precipitation of the salt would indicate the prevalence of arid climatic conditions at this time.

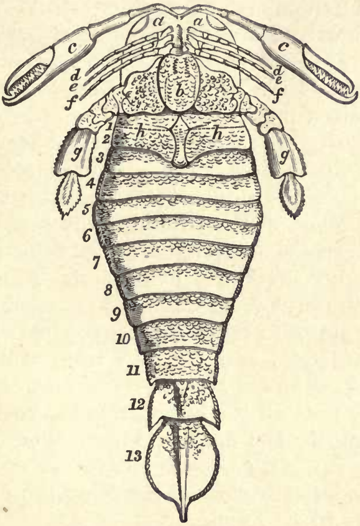


FIG. 215.—*Pterygotus.* (Restored by Dr H. Woodward.)

This uplift, as we have seen, was universal throughout North America and Northern Europe, and by changing the marine conditions of deposition that prevailed at the close of the mid-Silurian (=Salopian of Europe and Niagaran of North America) to brackish water and lacustrine, it introduced new conditions which led to the advent of the remarkable *Eurypterids.* These belonged to a type barely represented before; and they attained a size that would justify the surmise that they lived in a warm climate and possessed a plentiful supply of food.

In North America they are abundant in the *Waterlime Hydraulic Limestone*, the closing beds of the Salina Series.

Eurypterids appeared as suddenly and prominently in the top of the Silurian in Wales, England, Scotland, Sweden, and Russia as in North America, but in these regions there is no association of salt deposits. Nowhere are they associated with marine shells, and they range upward into the *Old Red Sandstone,* in which their associates are land plants and fishes.

Australasia.—Silurian rocks cover large tracts of country in New South Wales, Victoria, and Tasmania. They consist chiefly of sandstones, shales, quartzites, limestones, and cherts, which are frequently sharply tilted and folded. In many places the shales and limestones are richly fossiliferous. The fossils include trilobites, brachiopods, molluscs, corals, and bryozoans.

The celebrated Jenolan caves, to the west of the Blue, Mountains in New South Wales, occur in Silurian limestone.

Silurian rocks are present in South-West Tasmania, at Zeehan, and Queen River. They consist of sandstones, slates, and limestones, and contain a marine fauna.

The Silurian System in the South Island of New Zealand is represented by slates, quartzites, cherts, and limestones. Among the fossils in these rocks are numerous trilobites, brachiopods, corals, and bryozoans. Many of the trilobites and brachiopods are almost identical with species characteristic of the Silurian of England and North America, but singularly enough the New Zealand Silurian fauna is quite unlike the Australian. This would tend to show the existence in the Silurian period of a continuous sea-littoral between New Zealand, America, and North-West Europe, and of a deep sea or land barrier between New Zealand and Australia.

It is noticeable that all the known Silurian rocks in the Southern Hemisphere belong to the marine facies. The terrestrial or semi-terrestrial facies, with its characteristic fauna, which occupies such a conspicuous place in the close of the Silurian in Europe and North America, appears to be missing.

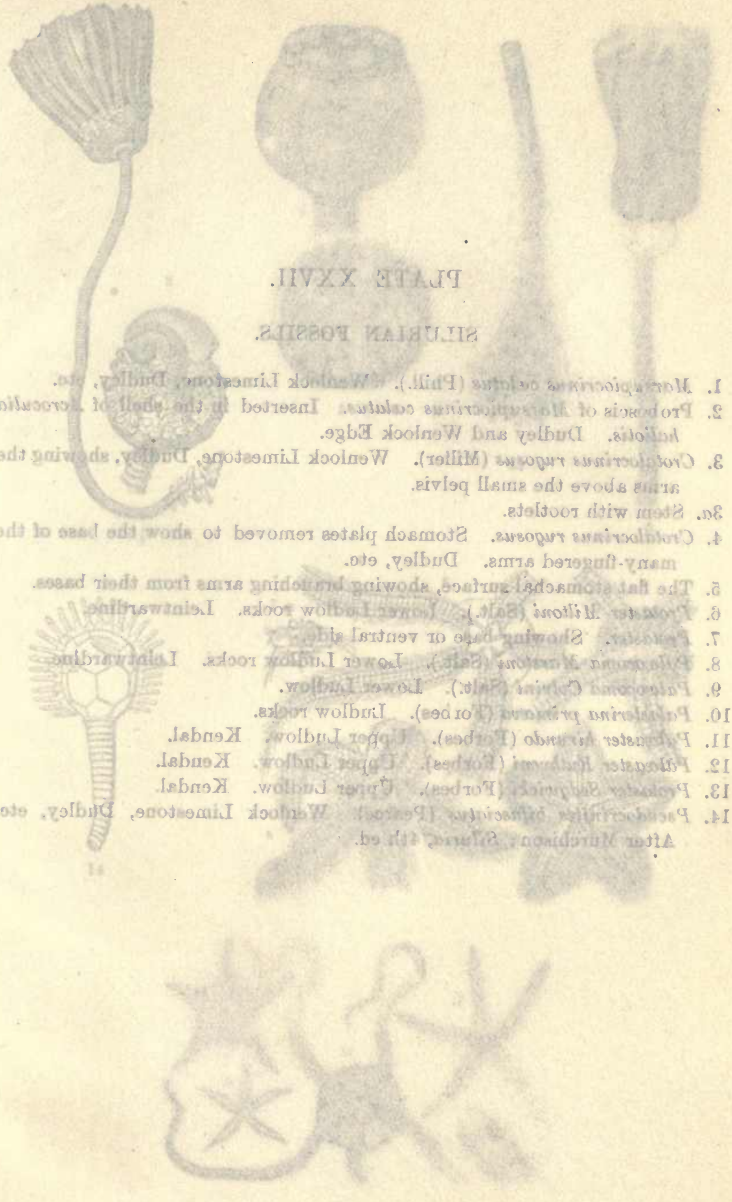
Economic Products.—The limestones of this system are valuable as a source of lime and as building-stone. The rock-salt and associated gypsum deposits in the State of New York are of great economic value. Elsewhere the Silurian rocks are not notable for their mineral contents.

SUMMARY.

(1) The lower Palæozoic is divided into three great systems, namely :—

3. Silurian.
2. Ordovician.
1. Cambrian.

1. These systems consist of a continuous succession of rocks that



SILURIAN FOSSILS.

PLATE XXVII.

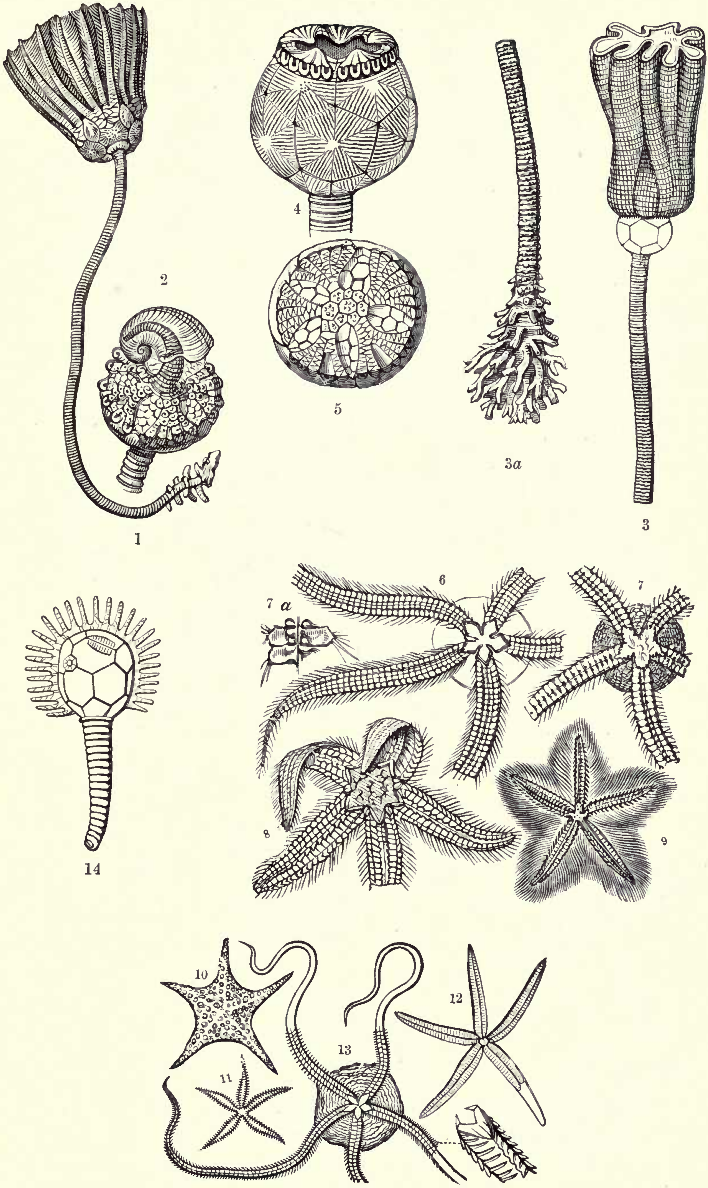
SILURIAN FOSSILS.

1. *Marsupiocrinus cœlatus* (Phill.). Wenlock Limestone, Dudley, etc.
2. Proboscis of *Marsupiocrinus cœlatus.* Inserted in the shell of *Acroculia haliotis.* Dudley and Wenlock Edge.
3. *Crotalocrinus rugosus* (Miller). Wenlock Limestone, Dudley, showing the arms above the small pelvis.

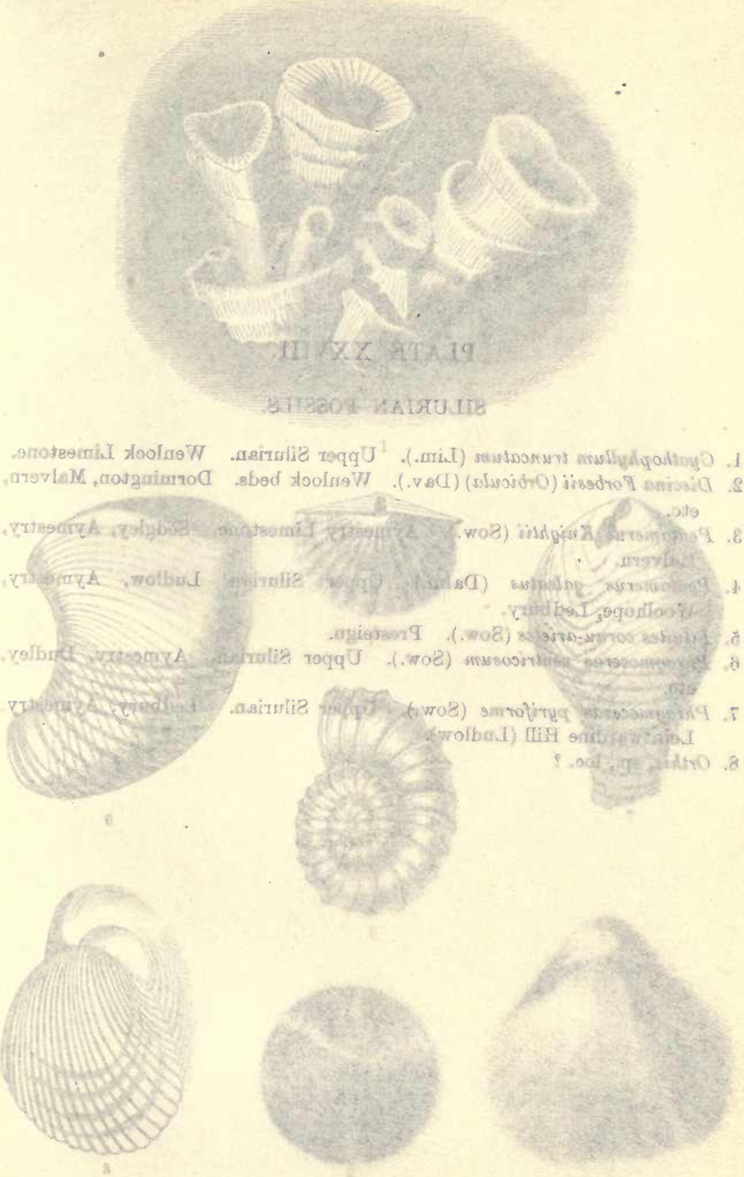
3*a*. Stem with rootlets.

4. *Crotalocrinus rugosus.* Stomach plates removed to show the base of the many-fingered arms. Dudley, etc.
5. The flat stomachal surface, showing branching arms from their bases.
6. *Protaster Miltoni* (Salt.). Lower Ludlow rocks. Leintwardine.
7. *Protaster.* Showing base or ventral side.
8. *Palæocoma Marstoni* (Salt.). Lower Ludlow rocks. Leintwardine.
9. *Palæocoma Colvini* (Salt.). Lower Ludlow.
10. *Palasterina primæva* (Forbes). Ludlow rocks.
11. *Palæaster hirundo* (Forbes). Upper Ludlow. Kendal.
12. *Palæaster Ruthveni* (Forbes). Upper Ludlow. Kendal.
13. *Protaster Sedgwicki* (Forbes). Upper Ludlow. Kendal.
14. *Pseudocrinites bifasciatus* (Pearce). Wenlock Limestone, Dudley, etc.

After Murchison; *Siluria*, 4th ed.



SILURIAN FOSSILS.

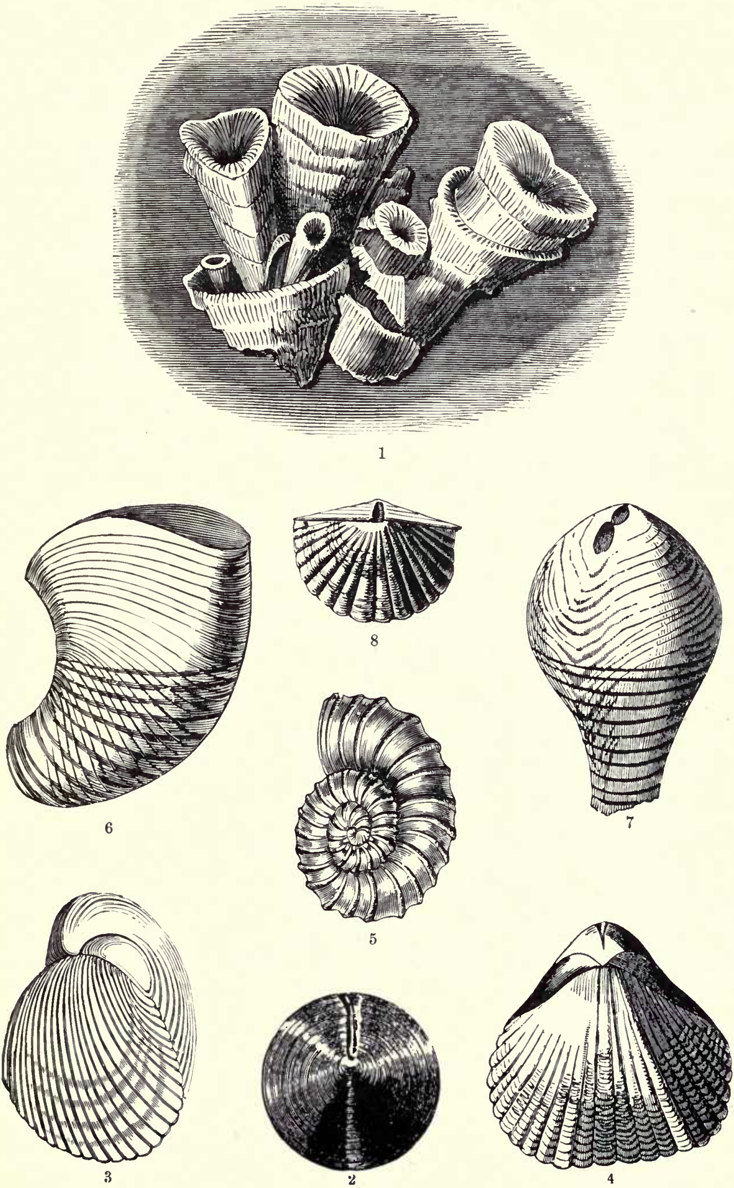


SILURIAN FOSSILS.

PLATE XXVIII.

SILURIAN FOSSILS.

1. *Cyathophyllum truncatum* (Lim.). Upper Silurian. Wenlock Limestone.
2. *Discina Forbesii* (*Orbicula*) (Dav.). Wenlock beds. Dormington, Malvern, etc.
3. *Pentamerus Knightii* (Sow.). Aymestry Limestone. Sedgley, Aymestry, Malvern.
4. *Pentamerus galeatus* (Dalm.). Upper Silurian. Ludlow, Aymestry, Woolhope, Ledbury.
5. *Lituites cornu-arietes* (Sow.). Presteign.
6. *Phragmoceras ventricosum* (Sow.). Upper Silurian. Aymestry, Dudley, etc.
7. *Phragmoceras pyriforme* (Sow.). Upper Silurian. Ledbury, Aymestry, Leintwardine Hill (Ludlow).
8. *Orthis*, sp., loc. ?



SILURIAN FOSSILS.

are normally conformable to one another. In many wide tracts in Europe and North America all three systems are present, following one another in orderly succession, but in other places there may be considerable breaks in the succession, and a system or portions of a system may be missing. These stratigraphical breaks are due to regional oscillations of the land.

2. The three systems are present in all the continents, and each is divisible into three groups, as follow :—

System.	British Isles.	North America.
Silurian	3. Ludlow Series.	3. Salina.
	2. Wenlock Series.	2. Niagaran.
	1. Llandovery Series.	1. Oswegan.
Ordovician	3. Caradoc or Bala.	3. Cincinnatian.
	2. Llandeilo.	2. Mohawkian.
	1. Arenig.	1. Canadian.
Cambrian	3. Olenus Beds.	3. Potsdam.
	2. Paradoxides Beds.	2. Acadian.
	1. Olenellus Beds.	1. Georgian.

3. The fauna preserved as fossils in the great pile of sediments comprising the Cambrian, Ordovician, and Silurian, shows a closely related facies throughout, as might be expected in the life inhabiting a continuous sea.

4. The life of each system (or period) is dominated by trilobites and graptolites, which appear suddenly in the Cambrian, attain their greatest development in the Ordovician, and begin to wane in the Silurian.

Besides trilobites and graptolites, there is a rich mixed fauna of corals, bryozoans, echinoderms, brachiopods, and molluscs.

5. In Northern Europe and North America, after the mid-Silurian, there began an upward movement which culminated in the *Old Red Sandstone* (Devonian) period. At the close of the Silurian this uplift enclosed great lakes and inland seas, particularly in eastern North America, where the drying up of the enclosed sea-basin led to the formation of valuable deposits of rock-salt.

The brackish-water conditions arising from the uplift led to the advent of a remarkable group of crustaceans, which included among other forms the gigantic *Pterygotus*.

CHAPTER XXV.

DEVONIAN SYSTEM.

The name Devonian was first applied by Murchison and Sedgwick to a great succession of greywackes, slates, and limestones occurring in the counties of Devon and Cornwall.

Marine and Lacustrine Types.—The Devonian System is characterised by the presence of two distinct facies of deposits, namely, a *marine* and a *lacustrine*.

The marine type or facies forms continuous sheets of great extent, and is found in all parts of the globe; while the terrestrial, or continental as it is sometimes called, occurs in disconnected areas, and is mostly confined to the British Isles, Western and Northern Europe.

The marine type of deposits was laid down on the floor of seas that were a continuance of the Silurian seas, and the continental type in basins situated in regions where denudation was extremely active.

The marine Devonians comprise the usual succession of sandstones, grits, slates, and limestones, and contain a mixed fauna of trilobites, molluscs, brachiopods, and corals, that do not differ in general character from the fauna of the Silurian. The continental type, on the other hand, consists mainly of brightly coloured red and brown sandstones and marls that contain no brachiopods or corals, but a fauna characterised by the presence of the giant Eurypterids, land plants, and armoured fishes.

The marine facies of rocks is usually called the *Devonian* type, and the continental or lacustrine, the *Old Red Sandstone* type.

Very few fossils are common to the two types, which are nevertheless believed to be contemporaneous on stratigraphical evidence.

In Devon and Cornwall the Devonian succession lies between the Silurian and Carboniferous, and passes conformably into the latter. In France, Belgium, North Germany, North Russia, and Southern Europe rocks of Devonian age also lie between the Silurian and Carboniferous.

In Scotland the Old Red Sandstone passes upward into the Carboniferous, and in Wales it passes downward into the Silurian and upward into the Carboniferous.

The stratigraphical evidence would thus seem to show conclusively that the marine Devonian rocks are the equivalent of the continental Old Red Sandstone Series.

Conditions of Deposition.—The differential uplift, which began in the mid-Silurian, continued into the next period ; and in Scotland, Ireland, and South Wales, owing to the peculiar configuration of the land, was able to enclose large inland basins in which the deposition of sediments took place contemporaneously with the deposition of sediments in the neighbouring seas.

Most of the basins were completely detached from the sea, but others were situated near the sea-coasts in situations where minor oscillations of the land sometimes permitted the sea to invade the basins.

As the uplift was differential and faster in Scotland than in the south, the inland basins came into existence in Scotland some time before those in Wales.

The Caledonian Movement.—There is abundant evidence of considerable differential movement in some parts of Western Europe during the early Palæozoic period. In the Southern Uplands of Scotland the Ludlow Series and Passage Beds are absent, while in the North-West Highlands the Silurian is entirely missing.

We may therefore infer that the final folding and ridging up of the Highlands took place after the close of the Ordovician and before the advent of the Carboniferous period ; and it first affected the North-West Highlands, and afterwards the Southern Uplands, where, as we have observed, only a portion of the Silurian is absent.

The effects of this folding and differential uplift can be traced in the Lake District, Isle of Man, and North Wales.

This movement or series of movements, usually known as the *Caledonian*, ridged the rocks into a number of approximately parallel folds which run from north-east to south-west. It constitutes one of the dominant structural features of the British Isles, and its effects are at once seen when we examine a geological map of the United Kingdom, for nearly all the boundaries of the older geological formations in Scotland, North-East Ireland, the Lake District, and North Wales have an approximate north-east and south-west bearing. Moreover, the Caledonian folds can be traced into Norway.

These crustal folds produced mountain-chains, of which the present mountains of the Scottish Highlands and Norway are but the worn-down and dissected stumps. At the same time a great tract of land appeared in North-West Europe which played an important part in the subsequent history of the Palæozoic.

Distribution.—In the British Isles the marine Devonian is most fully developed in Cornwall, Devon, and West Somerset.

The Old Red Sandstone occupies a triangular area in South Wales, north-west of the Severn. It also occurs in the Cheviot Hills; and further north forms a broad belt which runs across the island from the Firth of Clyde to the Forfar coast. A considerable tract occurs around the Moray Firth, and practically the whole of the county of Caithness and the Orkney Islands is occupied by the Old Red Sandstone.

In North Ireland the Old Red Sandstone is well developed in the counties of Tyrone and Fermanagh, and in South-West Ireland it forms the greater portion of the mountains of the province of Munster, and occupies nearly all the south-west corner of the island.

In Central Europe only the marine Devonian facies is represented. A large tract of these rocks extends from the north of France, through the broken and wooded Ardennes to the south of Belgium, and thence into Rhenish Prussia, Westphalia, and Nassau. They even pass as far east as the Harz Mountains and Thuringia.

In Southern Europe the Devonian covers a considerable area in Spain and Portugal.

In Russia it occupies an area many thousand square miles in extent, and stretches from Kurland through Livonia to the White Sea. There is also a wide development in the Urals, Siberia, Altai Mountains, South-West China, Asia Minor, and Turkish Bosphorus.

The Devonian rocks also cover large tracts in North and South Africa. In South Africa the rocks of this age, known as the *Cape System*, play an important part in the structure of Cape Colony and Natal.

No rocks of Devonian age have so far been recognised in India, but in Australia the marine type occupies extensive tracts in Queensland, New South Wales, Victoria, Western Australia, and Tasmania.

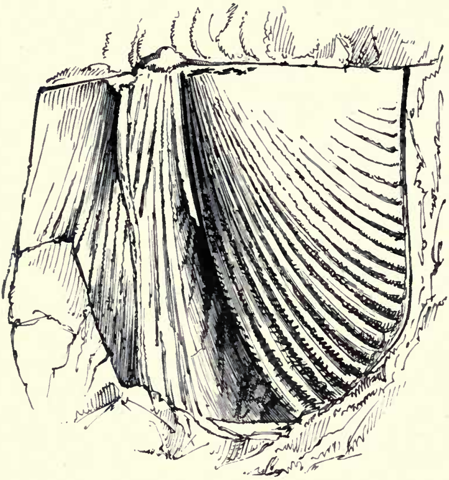
In North America the Devonians are well represented in the Appalachian Mountains of New York, in the States bordering the Great Lakes, in Ontario and Nova Scotia, in Arizona, Colorado, Utah, Nevada, Wyoming, Montana, North and South California, and many parts of Alaska.

Rocks.—The rocks of the marine or Devonian facies are mostly sandstones, conglomerates, grits, shales or slates, and limestones; and of the Old Red Sandstone type, red and brown sandstones, and marls.

The total thickness of the English Devonian is about 8000 feet, and of that of Central Europe 20,000 feet.

The Devonian was generally a period of comparative tranquillity except in Great Britain and Central Europe.

[PLATE XXIX.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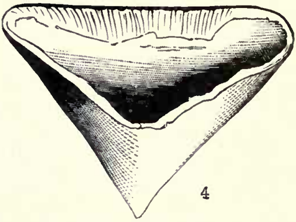
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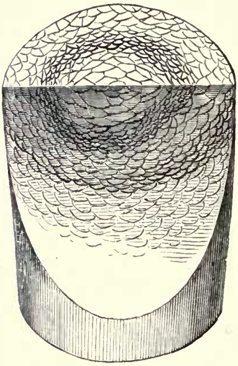
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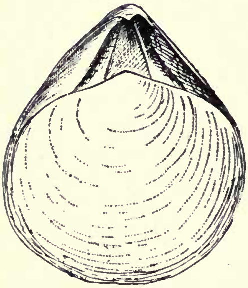
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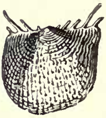
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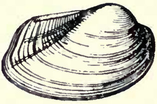
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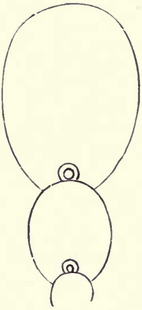
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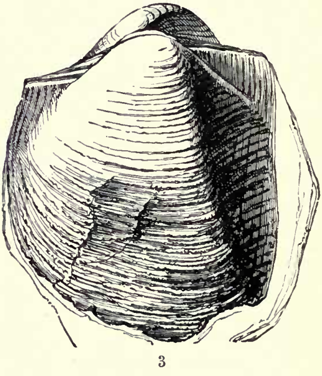
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DEVONIAN FOSSILS.

PLATE XXIX.

DEVONIAN FOSSILS.

1. *Spirifer disjuncta* (Sow.). Middle and Upper Devonian. British and Foreign.
2. *Stringocephalus Burtini* (Def.). Middle Devonian.
3. *Cucullæa trapezium* (Sow.). Middle and Upper Devonian.
4. *Calceola sandalina* (Lim.). Middle Devonian.
5. *Cyrtoceras tridecimale* (Phill.). Middle Devonian.
6. *Murchisonia spinosa* (Phill.). Middle Devonian.
7. Section of *Clymenia lævigata*, showing position of siphuncle at base of chamber.
8. *Cucullæa Hardingii* (Sow.). Middle and Upper Devonian.
9. *Strophalosia productoides* (Murch.). Middle and Upper Devonian.
10. Head of *Phacops granulatus* (Münst.). Upper Devonian.
11. *Cystiphyllum vesiculosum* (Goldf.). Coral, and characteristic of the Middle Devonian.

DEVONIAN FOSSILS.

In Scotland the Old Red Sandstone is intercalated with vast masses of andesitic lavas, tuffs, and agglomerates, from which we gather that the continental movement was in Britain accompanied by intense volcanic activity. The volcanic outbursts took place during the first half of the Old Red Sandstone period. The greatest eruptions occurred in the Cheviot Hills and in the Midland Valley, which stretches across the country from the north-east to south-west between the Highlands and the Southern Uplands. In this region the hard masses of lava and agglomerate stand up as conspicuous ridges, as in the Ochil and Sidlaw Hills. The aggregate thickness of the igneous rocks in Scotland is believed to be about 6000 feet.

In Germany and Devon the marine Devonians contain a large proportion of igneous material, mostly diabase and diabase tuffs. These rocks occur in many separate horizons, showing that the eruptions were separated by intervals of rest.

Fauna.—The general character of the Devonian marine fauna is similar to that of the Silurian, and many of the characteristic Silurian genera still survive.

Graptolites are entirely absent, the last of them being seen in the Ludlow Beds.

Corals and crinoids are still abundant, but the former show a marked decrease as compared with the Silurian.

Brachiopods are numerous, and represented by the genera *Spirifer* (Plate XXIX.), *Rhynchonella*, *Atrypa* (Plate XXIX.), *Chonetes*, *Stringocephalus* (Plate XXIX.), and *Uncites*, the last two being limited to the Devonian. *Productus* appears for the first time.

Molluscs are still abundant, although the gasteropods now occupy a subordinate place ; while the cephalopods show a notable advance, being represented by many old forms and a new type, the lobate-sutured *Goniatites*.

The trilobites show a decline in England both in number of genera and species, and those that survive exhibit a tendency to develop into the spiny, highly ornamented forms which are regarded as degenerate types of Crustacea.

In North America the trilobites present a notable increase over the number of species appearing in the same region in the Silurian epoch, but, as in England, the ornamented forms are conspicuous.

The Old Red Sandstone rocks contain very few fossils, but in a few places in Scotland the giant *Eurypterus* and *Pterygotus* are found in great abundance associated with the remains of land-plants and fishes.

Many of the fishes are protected with large bony plates that form a more or less rigid coat of armour. Among the genera so protected are *Pterichthys*, *Cephalaspis*, and *Coccosteus*.

The plants are principally Lycopods and ferns, which are represented by the genera, *Knorria* and *Palæopteris*.

The Old Red Sandstone also contains a freshwater mussel, *Anodonta Jukesii* (Plate XXXI. fig. 4), which closely resembles living species.

Subdivisions.—The marine Devonian rocks of North Devon are divided into eight groups of beds as follow :—

Upper Devonian	8. Pilton Beds. 7. Baggy Beds. 6. Pickwell Down Sandstone.
Middle Devonian	5. Morte Slates. 4. Ilfracombe Beds.
Lower Devonian	3. Hangman Grits. 2. Lynton Slates. 1. Foreland Sandstone.

The strata are so much disturbed by folding and faulting that there is still some doubt as to the correct order of succession of the beds.

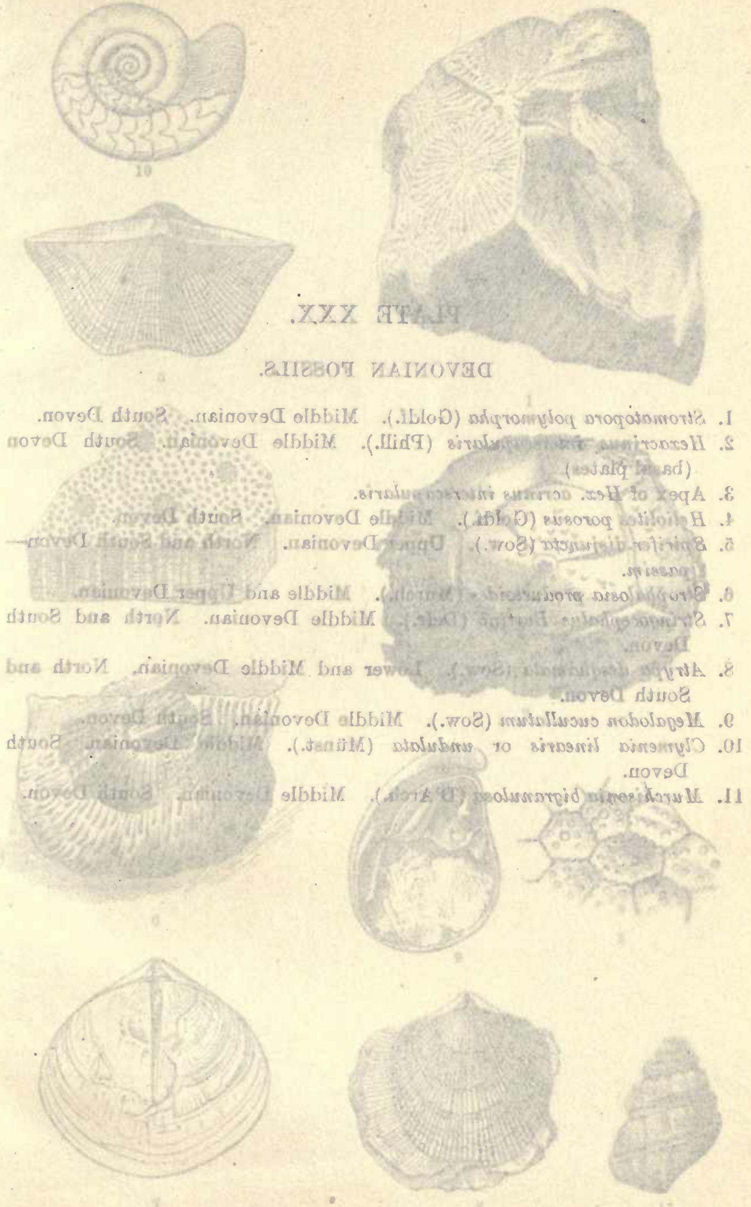
Fossils are numerous in the limestones, scarce in the slates, and usually absent in the sandstones. The limestones and slates are marine and the sandstones probably estuarine.

Perhaps some of the sandstones were formed in brackish-water basins near the sea in conditions not dissimilar to those in which some portions of the Old Red Sandstone were laid down.

In the Pickwell Down Sandstone beds, which are red and purple in colour, there are found the remains of fishes and land plants. A few of the fishes are characteristic of the Old Red Sandstone, the commonest genus being *Pteraspis*, which first appeared in the Upper Ludlow towards the close of the Silurian.

The weight of the evidence would seem to support the view that the conditions of deposition of the Pickwell Down Sandstone were related to those of the Mediterranean type.

In Scotland the Old Red Sandstone is divided into two groups, an Upper and a Lower Series, which are separated by a well-marked unconformity ; but it should be noted that recent research tends to show that a portion of the Lower Series may belong to the Silurian, and a portion of the Upper Series to the Carboniferous. It would seem from this that the Old Red Sandstone conditions appeared in Scotland earlier than in South Wales, and ended later ; and this is what we should look for, since the uplift, which we know began after the mid-Silurian, was differential, being faster in North Britain than in England. As a natural consequence of this the terrestrial or continental conditions of deposition

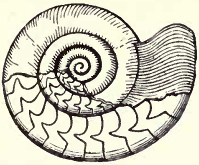


DEVONIAN FOSSILS.

PLATE XXX.

DEVONIAN FOSSILS.

1. *Stromatopora polymorpha* (Goldf.). Middle Devonian. South Devon.
2. *Hexacrinus interscapularis* (Phill.). Middle Devonian. South Devon (basal plates).
3. Apex of *Hex. acrinus interscapularis.*
4. *Heliolites porosus* (Goldf.). Middle Devonian. South Devon.
5. *Spirifer disjuncta* (Sow.). Upper Devonian. North and South Devon—*passim.*
6. *Strophalosia productoides* (Murch.). Middle and Upper Devonian.
7. *Stringocephalus Burtini* (Defr.). Middle Devonian. North and South Devon.
8. *Atrypa desquamata* (Sow.). Lower and Middle Devonian. North and South Devon.
9. *Megalodon cucullatum* (Sow.). Middle Devonian. South Devon.
10. *Clymenia linearis* or *undulata* (Münst.). Middle Devonian. South Devon.
11. *Murchisonia bigranulosa* (D'Arch.). Middle Devonian. South Devon.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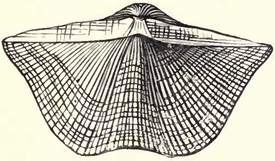
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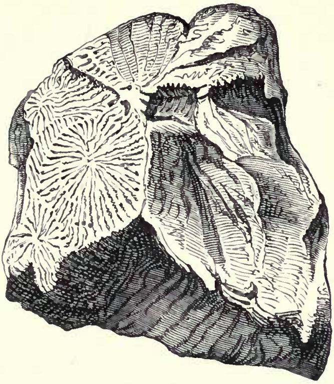
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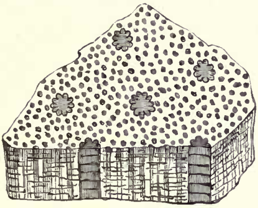
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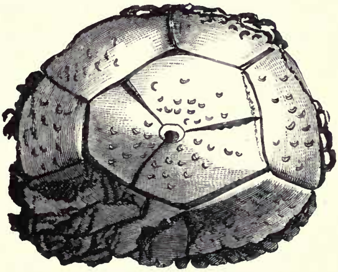
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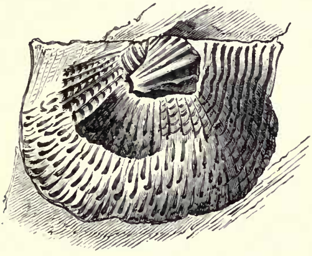
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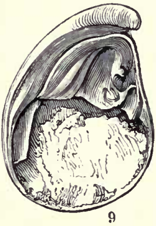
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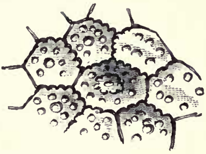
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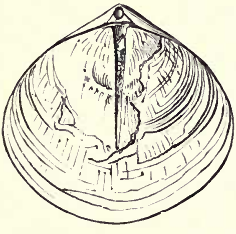
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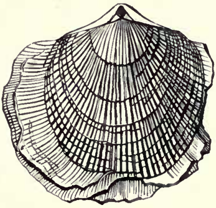
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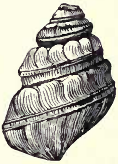
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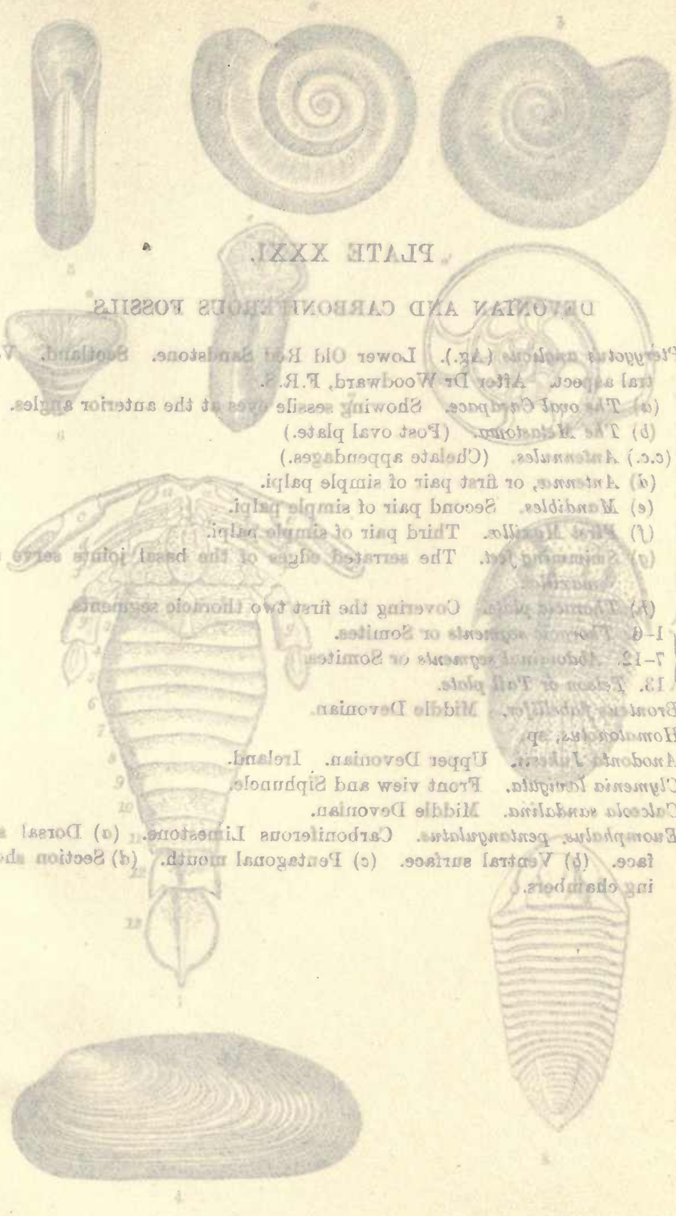
DEVONIAN FOSSILS.



DEVONIAN AND CARBONIFEROUS FOSSILS.

PLATE XXXI.

DEVONIAN AND CARBONIFEROUS FOSSILS.

1. *Pterygotus anglicus* (Ag.). Lower Old Red Sandstone. Scotland. Ventral aspect. After Dr Woodward, F.R.S.
    - (*a*) *The oval Carapace.* Showing sessile eyes at the anterior angles.
    - (*b*) *The Metastoma.* (Post oval plate.)
    - (*c.c.*) *Antennules.* (Chelate appendages.)
    - (*d*) *Antennæ*, or first pair of simple palpi.
    - (*e*) *Mandibles.* Second pair of simple palpi.
    - (*f*) *First Maxillæ.* Third pair of simple palpi.
    - (*g*) *Swimming feet.* The serrated edges of the basal joints serve as *maxillæ.*
    - (*h*) *Thoracic plate.* Covering the first two thoracic segments.
    - 1–6. *Thoracic segments* or Somites.
    - 7–12. *Abdominal segments* or Somites.
    - 13. *Telson or Tail plate.*
2. *Bronteus flabellifer.* Middle Devonian.
3. *Homalonotus*, sp.
4. *Anodonta Jukesii.* Upper Devonian. Ireland.
5. *Clymenia lævigata.* Front view and Siphuncle.
6. *Calceola sandalina.* Middle Devonian.
7. *Euomphalus pentangulatus.* Carboniferous Limestone. (*a*) Dorsal surface. (*b*) Ventral surface. (*c*) Pentagonal mouth. (*d*) Section showing chambers.

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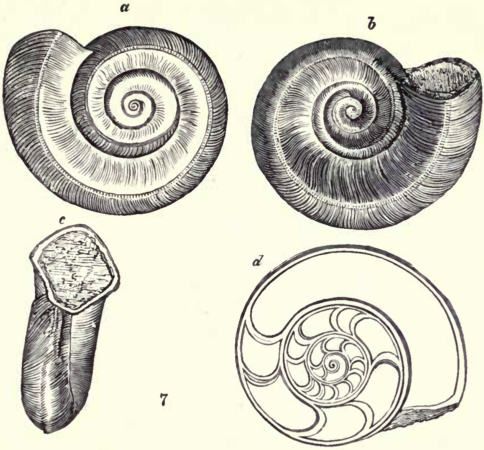

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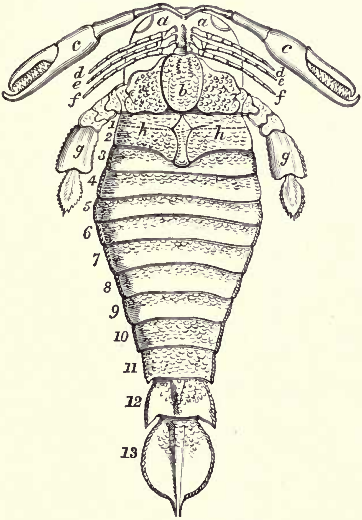

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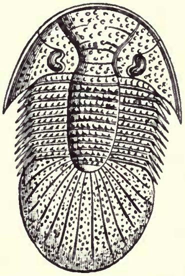

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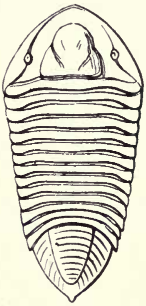

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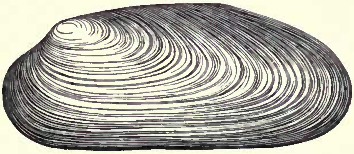

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Devonian and Carboniferous Fossils.

would obviously come into existence in the north sooner than in the south.

From the evidence before us we are led to infer that, as the uplift progressed, the sea retreated southward from the Caledonian region until it reached the ancient coasts of Devon, on the borders of which was formed a land-locked basin to which the sea had occasional access, and in which the Pickwell Down Sandstone was laid down.

The uplift had now reached its climax and was soon followed by subsidence which lasted until the basal limestones of the Carboniferous System were laid down. As the downward movement progressed, the sea advanced northward, and deposition of sediments began long before deposition could commence in the north. Obviously, then, the beds of the Lower Carboniferous laid down in the Devonian seas would be missing in the north.

Devonian rocks are more fully developed in Rhenish Prussia than elsewhere in Europe. They are arranged in a series of reversed folds, and their estimated thickness is 20,000 feet.

The Lower Devonian of this region consists mainly of sandy and clayey beds in which fossils are not abundant, the most common being brachiopods, among which the characteristic species are *Spirifer auriculatus*, *S. curvatus*, *S. paradoxus*, and *Chonetes dilatata*.

The Middle Devonian is mainly calcareous, and contains in the well-known *Calceola Beds* the rich fauna for which the Devonian of Eifel has become so famous. Among the typical forms are the Lamellibranchs *Stringocephalus Burtini* (Plate XXX. fig. 7) and *Megalodon cucullatum* (Plate XXX. fig. 9); the Gasteropods *Murchisonia bilineata* and *Pleurotomaria delphinuloides*; and the Cephalopods *Orthoceras triangulare* and *Goniatites gracilis*.

The Upper Devonian is chiefly represented by calcareous slates and limestones rich in fossils. Among the brachiopods are *Rhynchonella cuboides*, *Spirifer Verneuili*, and *Productus subaculeatus*. The ammonoid Cephalopod *Clymenia* is entirely limited to the upper part of the Upper Devonian.

The threefold division of the Devonian System recognised in North America is as follows:—

Upper Devonian (4000 to 8000 feet)	Chautauquan. Senecan.
Middle Devonian (1000 to 4500 feet)	Erian. Ulsterian.
Lower Devonian (300 to 2000 feet)	Oriskanian. Helderbergian.

By some American writers the Helderbergian limestones are referred to the Upper Silurian.

The North American Devonian rocks are mostly sandstones, conglomerates, shales, quartzites, and limestones. The shales, limestones, and many of the sandstones are marine. Some of the red sandstones, red shales, and conglomerates are estuarine or lacustrine. The Catskill Beds of New York and Pennsylvania, which represent the whole of the Upper Devonian, belong to the continental facies of rocks. They contain only a few freshwater and brackish-water forms.

The marine faunas possess the same general features as the European, but, unlike the European, are distinguished by a remarkable revival of the trilobites.

Economic Products.—The Upper Devonian is the chief source of the oil and gas in Pennsylvania and South-West New York, while the Middle Devonian is the oil-bearing series in Ontario. The Devonian shales of Central Tennessee contain valuable deposits of rock-phosphates. In Europe and the other continents the Devonian does not contain ores or minerals of much economic value.

CHAPTER XXVI.

CARBONIFEROUS SYSTEM.

This system contains the principal coal-deposits of the globe, and is therefore of vast economic value to mankind. The name Carboniferous came into use at a time when it was believed that no true coal existed in any other formation. It is now universally recognised as a time-name for all the clastic rocks that lie between the Devonian and Permian systems.

Distribution.—In Europe the Carboniferous System occupies large tracts in the British Isles, North France, Belgium, Westphalia, and Russia, where they lie conformably on the Devonian. In the Saarbrück district, Bohemia, and Russia, they pass upward without a break into the Permian; but as the result of local earth-movement, a break is found in some regions between the Lower and Upper Carboniferous.

A considerable development of this system also occurs in Southern Europe, notably on the south border of the Central Plateaux of France, in the Pyrenees, and Alps. The Carboniferous rocks cross the Mediterranean basin into North Africa and appear over a wide extent of country in the Western Sahara, in the hinterland of Morocco, in Eastern Egypt, East Sudan, Arabia, and South Palestine.

From Eastern Russia the Carboniferous System extends into Siberia, China, and Japan. In the province of Shansi, in Eastern China, the productive Coal-Measures of this age have been estimated by Richthofen to occupy an area of 35,000 square miles.

Carboniferous rocks are well developed in Northern India, but their greatest development in the Northern Hemisphere is in the United States and Alaska.

In the Southern Hemisphere Carboniferous rocks occupy wide tracts in Eastern Australia, South Africa, Peru, and Bolivia. They are also present in the Antarctic continent, but their extent in that region is at present unknown.

Rocks.—There are two distinct facies of rocks represented in the Carboniferous System in both hemispheres, namely, a marine and terrestrial. The marine dominates the Lower Carboniferous, and the terrestrial the Upper Carboniferous.

The marine facies consists mainly of limestones and shales; the terrestrial facies, of sandstones, conglomerates, grits, and shales with seams of coal and ironstone.

In Great Britain and Russia the Carboniferous rocks are comparatively undisturbed; but in North France, Belgium, and United States they are frequently sharply folded. In almost all the great coalfields the strata, even when lying horizontal, are intersected by numerous faults, some of which are of great magnitude.

In the British Isles, Western Europe, North India, and Australia, the Carboniferous rocks are intercalated with numerous sheets of lava and beds of tuff.

Fauna and Flora.—The fauna of the Lower Carboniferous

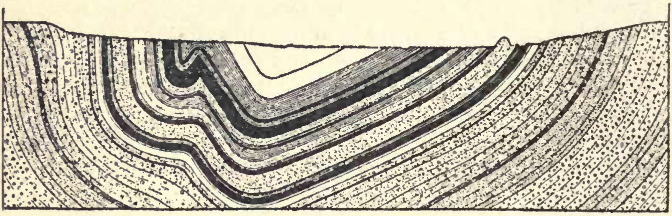


FIG. 215A.—Showing cross-section of the New Boston anthracite basin, Pennsylvania. (Penn. Geo. Survey.)

limestones is rich in corals, crinoids and brachiopods. Among the corals are the well-known genera *Lithostrotion*, *Cyathophyllum*, and *Syringopora*. The crinoids include many that have survived from the Devonian, and in addition we have the new genera *Actinocrinus* and *Woodocrinus*, both confined to this system.

Echinoderms are still plentiful; and brachiopods, which are numerous, are represented by *Productus*, *Spirifer*, *Athyris*, *Rhynchonella*, and *Terebratula*. The punctate *Spiriferina* is also common.

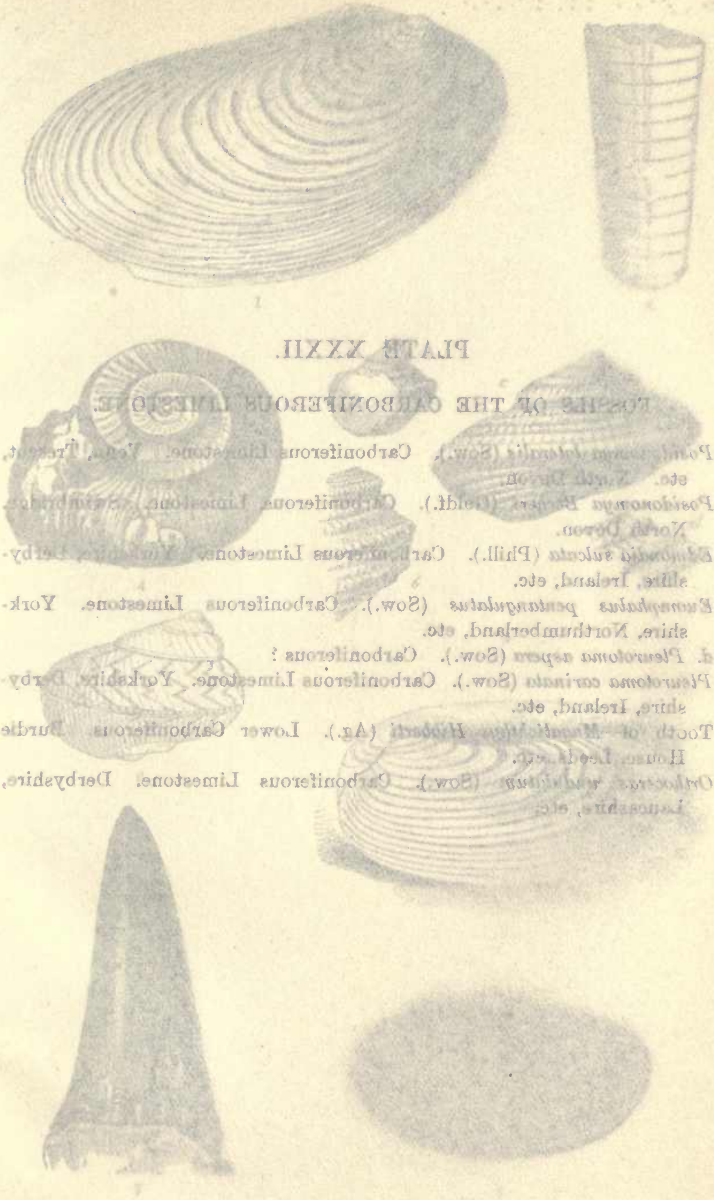
Molluscs are abundant, and the Cephalopods include *Orthoceras* and *Actinoceras*.

Trilobites make their last appearance in this system, and are represented by *Phillipsia* (Plate XXXIII. fig. 7) and other genera.

Sharks and other fishes are numerous and important.

Labyrinthodonts appear in the Lower Carboniferous. They are the earliest of the amphibians.

The land flora of the Upper Carboniferous is luxuriant and varied.



Fossils of the Carboniferous Limestone.

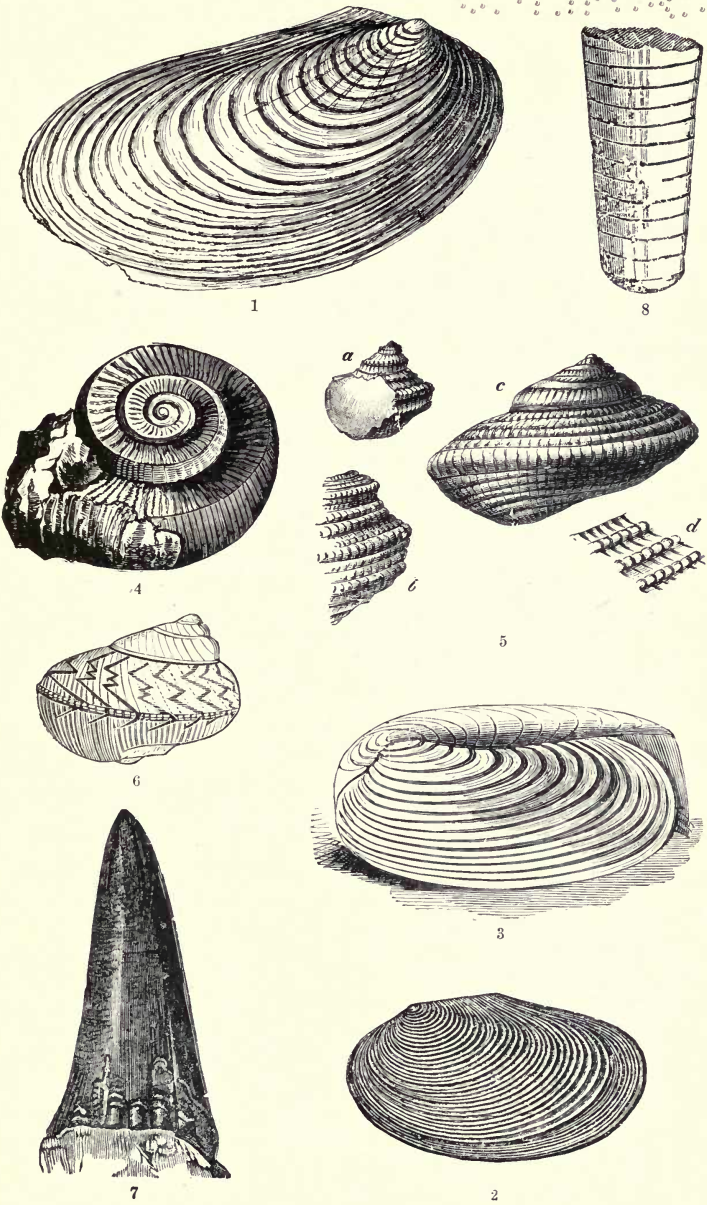
PLATE XXXII.

FOSSILS OF THE CARBONIFEROUS LIMESTONE.

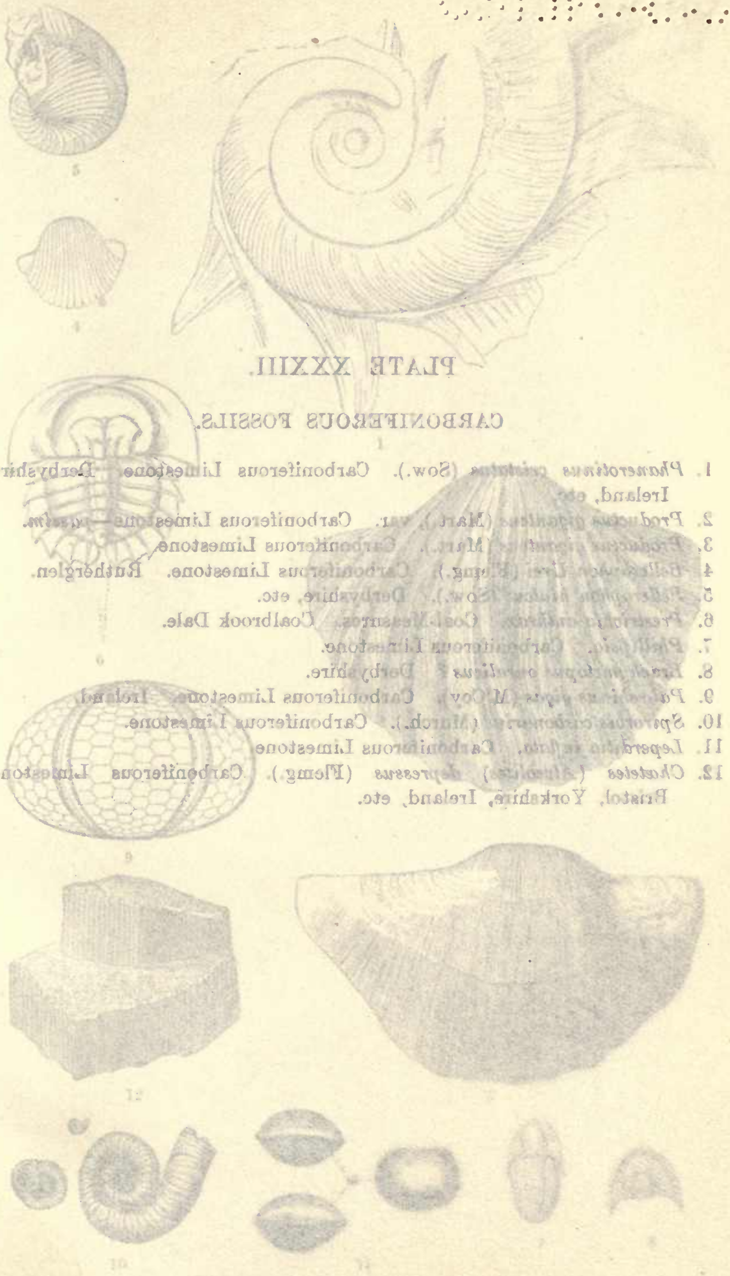
1. *Posidonomya lateralis* (Sow.). Carboniferous Limestone. Venn, Trescot, etc. North Devon.
2. *Posidonomya Becheri* (Goldf.). Carboniferous Limestone. Swimbridge. North Devon.
3. *Edmondia sulcata* (Phill.). Carboniferous Limestone. Yorkshire, Derbyshire, Ireland, etc.
4. *Euomphalus pentangulatus* (Sow.). Carboniferous Limestone. Yorkshire, Northumberland, etc.

5a-d. *Pleurotoma aspera* (Sow.). Carboniferous ?

6. *Pleurotoma carinata* (Sow.). Carboniferous Limestone. Yorkshire, Derbyshire, Ireland, etc.
7. Tooth of *Magalichthys Hibberti* (Ag.). Lower Carboniferous. Burdie House, Leeds, etc.
8. *Orthoceras undulatum* (Sow.). Carboniferous Limestone. Derbyshire, Lancashire, etc.



FOSSILS OF THE CARBONIFEROUS LIMESTONE.

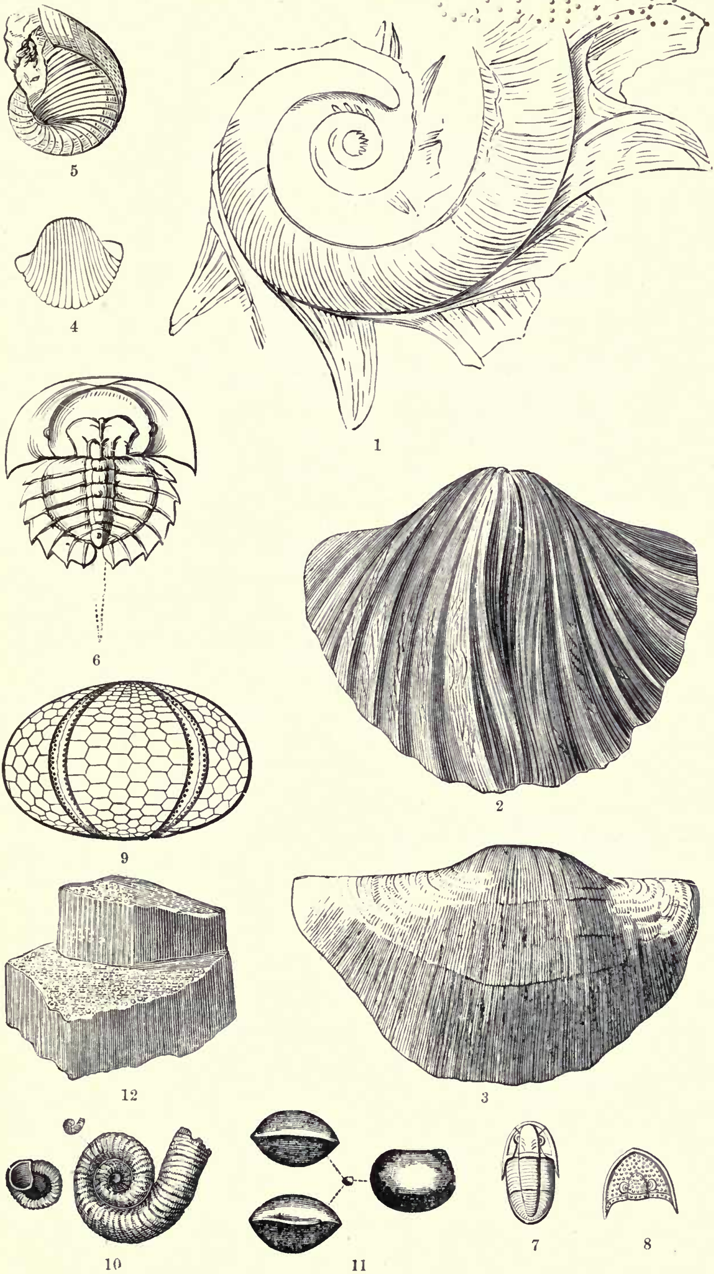


Carboniferous Fossils.

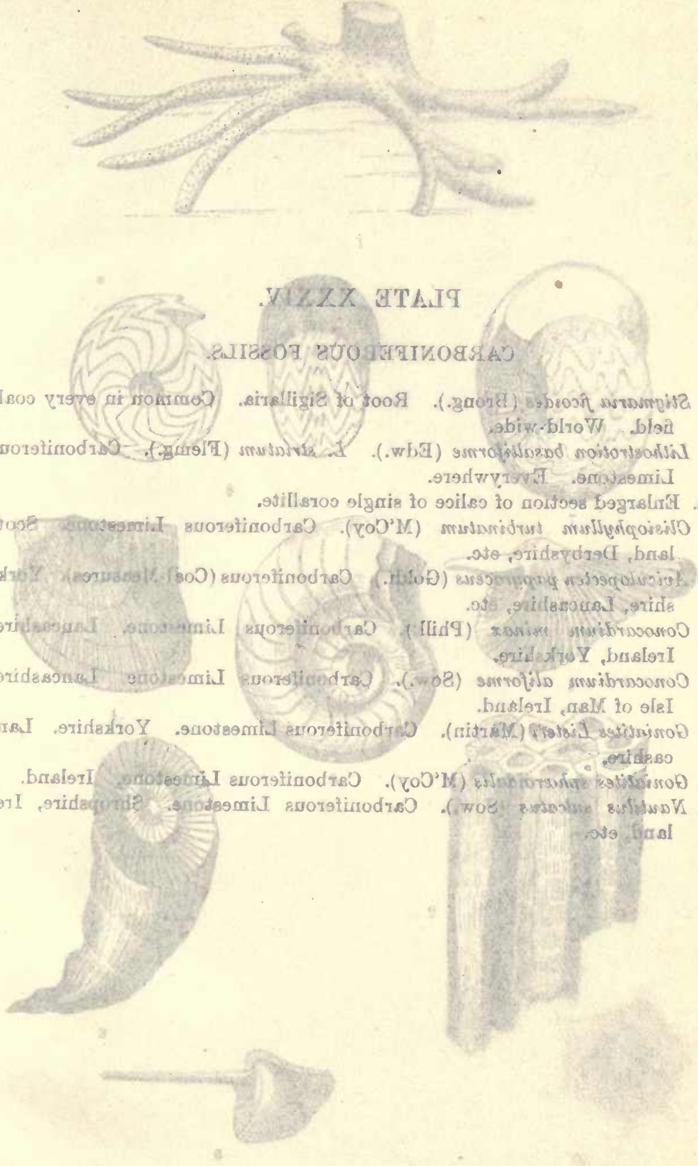
PLATE XXXIII.

CARBONIFEROUS FOSSILS.

1. *Phanerotinus cristatus* (Sow.). Carboniferous Limestone. Derbyshire, Ireland, etc.
2. *Productus giganteus* (Mart.), var. Carboniferous Limestone—*passim*.
3. *Productus giganteus* (Mart.). Carboniferous Limestone.
4. *Bellerophon Urei* (Flemg.). Carboniferous Limestone. Rutherglen.
5. *Bellerophon hiulcus* (Sow.). Derbyshire, etc.
6. *Prestrichia anthrax*. Coal-Measures. Coalbrook Dale.
7. *Phillipsia*. Carboniferous Limestone.
8. *Brachymetopus ouralicus ?* Derbyshire.
9. *Palæchinus gigas* (M'Coy). Carboniferous Limestone. Ireland.
10. *Spirorbis carbonarius* (Murch.). Carboniferous Limestone.
11. *Leperditia inflata*. Carboniferous Limestone.
12. *Chætetes* (*Alveolites*) *depressus* (Flemg.). Carboniferous Limestone. Bristol, Yorkshire, Ireland, etc.



CARBONIFEROUS FOSSILS.



Carboniferous Fossils.

PLATE XXXIV.

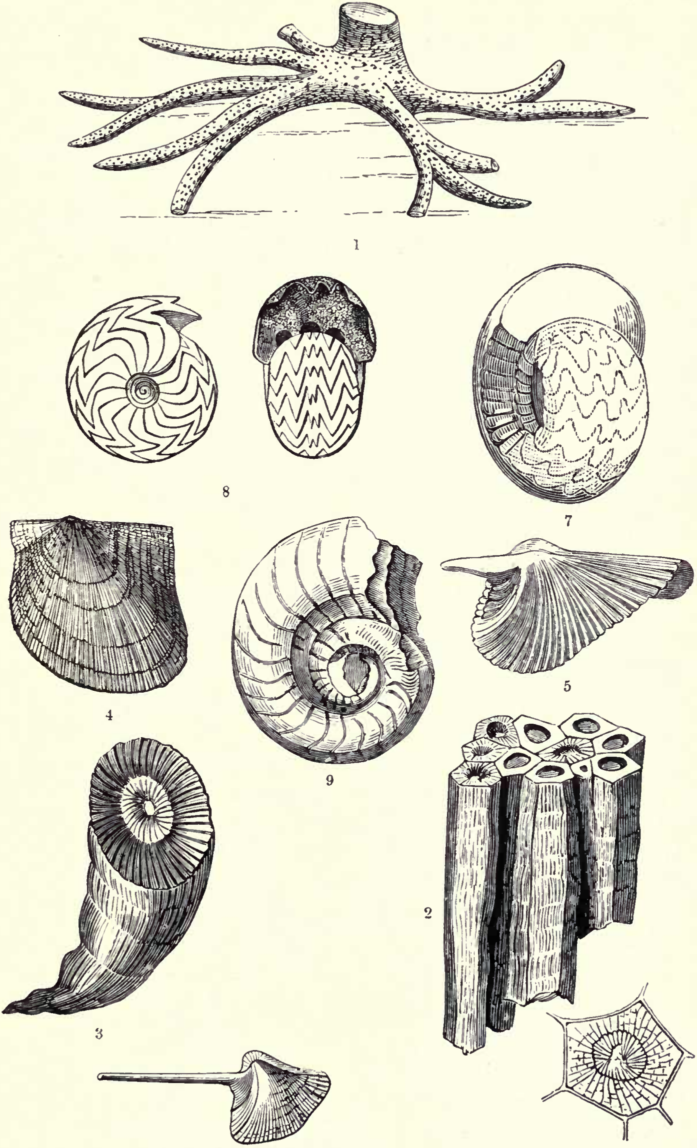
CARBONIFEROUS FOSSILS.

1. *Stigmaria ficoides* (Brong.). Root of Sigillaria. Common in every coalfield. World-wide.
2. *Lithostrotion basaltiforme* (Edw.). *L. striatum* (Flemg.). Carboniferous Limestone. Everywhere.

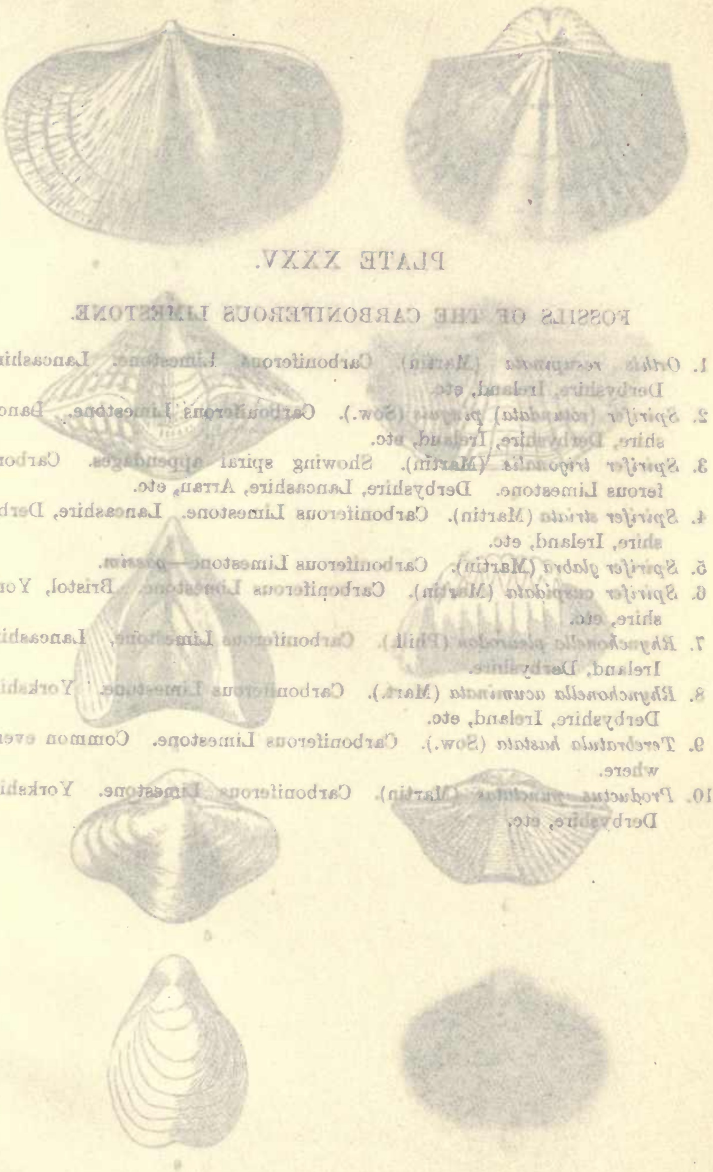
2*a*. Enlarged section of calice of single corallite.

3. *Clisiophyllum turbinatum* (M'Coy). Carboniferous Limestone. Scotland, Derbyshire, etc.
4. *Aviculopecten papyraceus* (Goldf.). Carboniferous (Coal-Measures). Yorkshire, Lancashire, etc.
5. *Conocardium minax* (Phill.). Carboniferous Limestone. Lancashire, Ireland, Yorkshire.
6. *Conocardium aliforme* (Sow.). Carboniferous Limestone. Lancashire, Isle of Man, Ireland.
7. *Goniatites Listeri* (Martin). Carboniferous Limestone. Yorkshire. Lancashire.
8. *Goniatites sphæroidalis* (M'Coy). Carboniferous Limestone. Ireland.
9. *Nautilus sulcatus* (Sow.). Carboniferous Limestone. Shropshire, Ireland, etc.

[Plate XXXIV.



Carboniferous Fossils.

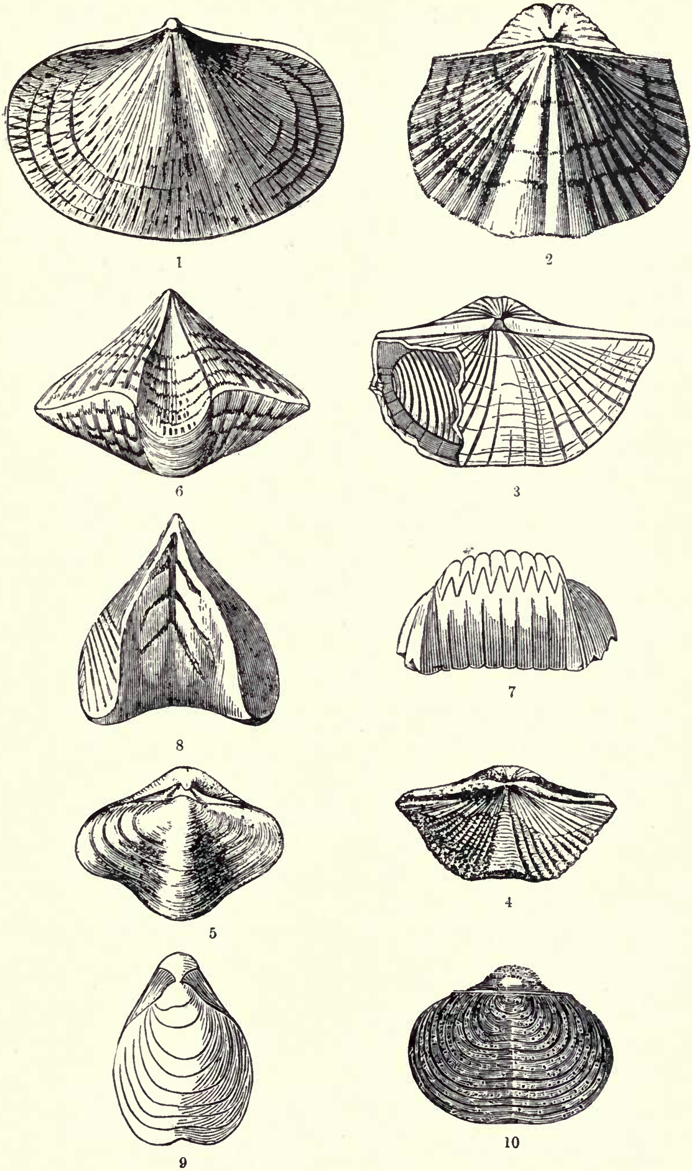


Fossils of the Carboniferous Limestone.

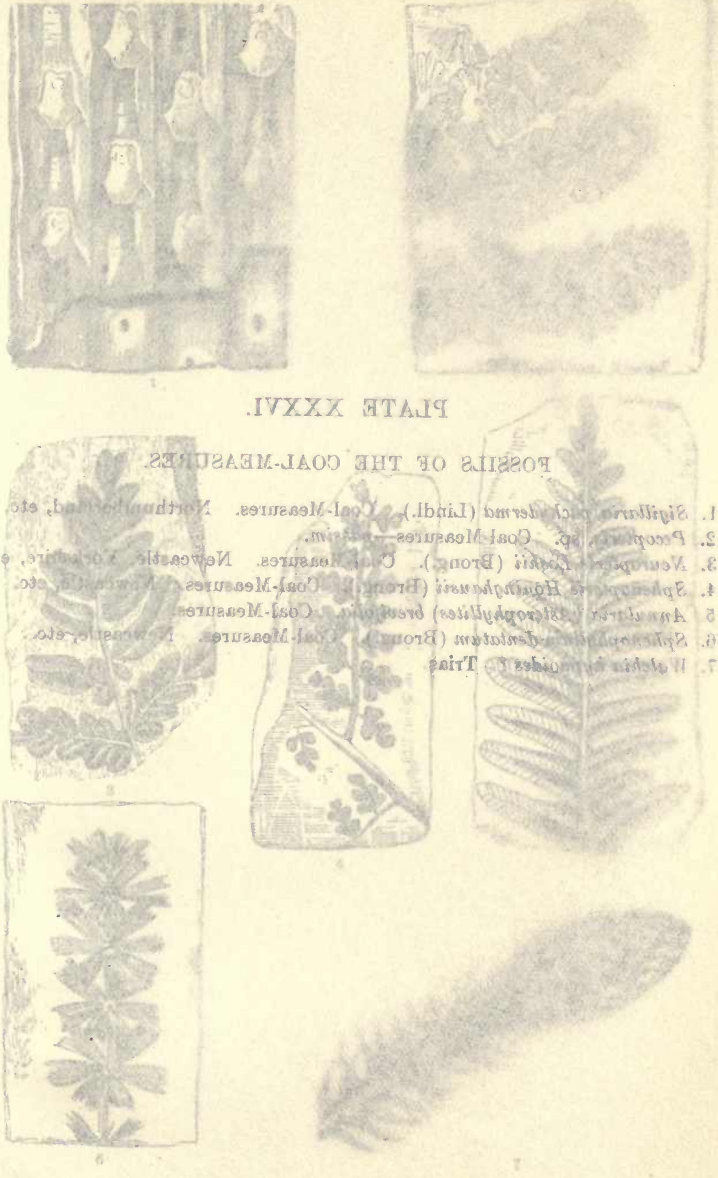
PLATE XXXV.

FOSSILS OF THE CARBONIFEROUS LIMESTONE.

1. *Orthis resupinata* (Martin). Carboniferous Limestone. Lancashire, Derbyshire, Ireland, etc.
2. *Spirifer* (*rotundata*) *pinguis* (Sow.). Carboniferous Limestone. Lancashire, Derbyshire, Ireland, etc.
3. *Spirifer trigonalis* (Martin). Showing spiral appendages. Carboniferous Limestone. Derbyshire, Lancashire, Arran, etc.
4. *Spirifer striata* (Martin). Carboniferous Limestone. Lancashire, Derbyshire, Ireland, etc.
5. *Spirifer glabra* (Martin). Carboniferous Limestone—*passim.*
6. *Spirifer cuspidata* (Martin). Carboniferous Limestone. Bristol, Yorkshire, etc.
7. *Rhynchonella pleurodon* (Phill.). Carboniferous Limestone. Lancashire, Ireland, Derbyshire.
8. *Rhynchonella acuminata* (Mart.). Carboniferous Limestone. Yorkshire, Derbyshire, Ireland, etc.
9. *Terebratula hastata* (Sow.). Carboniferous Limestone. Common everywhere.
10. *Productus punctatas* (Martin). Carboniferous Limestone. Yorkshire, Derbyshire, etc.



Fossils of the Carboniferous Limestone.

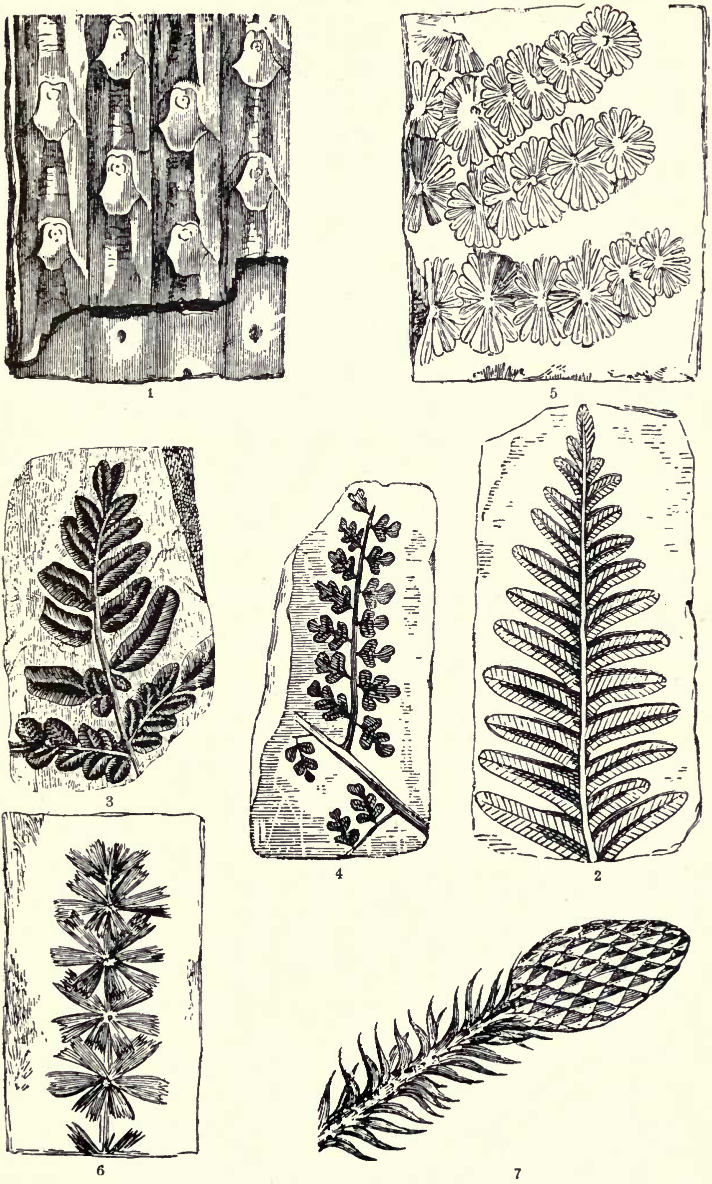


Fossils of the Carboniferous Coal-Measures.

PLATE XXXVI.

FOSSILS OF THE COAL-MEASURES.

1. *Sigillaria pachyderma* (Lindl.). Coal-Measures. Northumberland, etc.
2. *Pecopteris*, sp. Coal-Measures—*passim.*
3. *Neuropteris Loshii* (Brong.). Coal-Measures. Newcastle, Yorkshire, etc.
4. *Sphenopteris Höninghausii* (Brong.). Coal-Measures. Newcastle, etc.
5. *Annularia* (*Asterophyllites*) *brevifolia.* Coal-Measures.
6. *Sphenophyllum dentatum* (Brong.). Coal-Measures. Newcastle, etc.
7. *Walchia hypnoides ?* Trias.



FOSSILS OF THE CARBONIFEROUS COAL-MEASURES.

It is specially characterised by the prevalence of gigantic Lycopods or club-mosses, ferns and fern allies, and horse-tails, all of which grew to the size of forest trees.

Of the Lycopods the principal genera are *Lepidodendron* and *Sigillaria* (Plate XXXVI. fig. 1), both of which attained a height of 100 feet. *Stigmaria*, at one time believed to be a distinct genus, is the name applied to the roots of various Lycopods.

Among the equisetums, the most important genera are *Calamites* and *Annularia*.

The fern-like forms of vegetation include *Sphenopteris* (Plate XXXVI. fig. 4), *Neuropteris* (Plate XXXVI. fig. 3), *Pecopteris* (Plate XXXVI. fig. 2), and *Alethopteris Sphenophyllum dentatum* is also characteristic (Plate XXXVI. fig. 6).

The gymnosperms are represented by *Cordaites* and *Conifers*.

The lower portion of the Upper Carboniferous is frequently marine, and, in some regions, marine beds are intercalated with the terrestrial beds. The fauna in these marine beds is mainly composed of molluscs, among which Lamellibranchs, Gasteropods, and Cephalopods are well represented, among the first being *Nucula oblonga*, *Nuculana acuta*, and *Pterinopecten papyraceus*, and among the last *Gastrioceras carbonarium* and *Goniatites Listeri* (Plate XXXIV. fig. 7).

Conditions of Deposition.—In the British Isles a downward movement set in at the close of the Devonian; but as we have already observed, the uplift of the preceding period was differential, being greatest in the north and least in the south, so that when the Carboniferous period began, the conditions of deposition in the south of England were still marine.

As the subsidence progressed, the sea once more began to advance slowly northward; but the basal calcareous deposits of the Carboniferous were laid down in the Devon region before the sea had reached the Midlands, or deposition had commenced in the north. Hence the basal beds of the Lower Carboniferous laid down in Devon are older than the basal beds further north by the time it took the sea to advance to the northern regions.

When traced northward the Lower Carboniferous beds of the south decrease in thickness and finally disappear. Thus, in the coalfields of South Staffordshire and Warwickshire, the Lower Carboniferous is either absent or but feebly represented; and where the Upper Carboniferous rests directly on the older rocks, we have a striking example of the overlap of strata due to subsidence.

While marine limestones were being deposited in the south of England, deposition was still in progress in the inland basins of the north; that is, in the Old Red Sandstone basins. Thus it happens that while the Lower Carboniferous of South England consists of marine limestones, the contemporaneous beds in Scotland are mainly red and yellow sandstones and shales with coal-seams; that is, rocks of the Old Red Sandstone facies. These beds are, in their upper division, intercalated with bands of limestone, some of which are marine and some freshwater. The lowest of the marine limestones marks the date when the advancing sea invaded the Caledonian basins; while the underlying lacustrine sandstones and shales are a record of the time it took the sea to advance to that region.

As soon as a continuous sea was established, deposition proceeded on a continuous sea-floor from south to north, the deposits being everywhere marine and contemporaneous. Hence it follows that the upper portion of the Lower Carboniferous of South England may be correlated with the Calcareous (Carboniferous Limestone) Series at the top of the Lower Carboniferous in Scotland.

The Millstone Grit, which follows the Mountain Limestone, is a littoral deposit. From this we learn that the downward movement was arrested about the close of the Upper Carboniferous, and immediately followed by a general uplift, which not only affected the British Isles, but also the whole of Northern Europe and North America.

The Millstone Grit is succeeded by the Coal-Measures of deltaic and terrestrial origin from which we further gather that the uplift continued until there was an approach to the continental conditions of the Old Red Sandstone period. That is, the land was uplifted until large inland basins were enclosed, many of them possessing connection with the open sea in some direction.

The succession of coal-seams that exists in some of the coal basins tends to show that many minor oscillations of the land took place towards the close of the Carboniferous period.

The close of the Carboniferous witnessed great crustal movements throughout Western and Central Europe, where there is a marked stratigraphical break between the Carboniferous and Permian.

Summarising the above, we find that, at the beginning of the Carboniferous period, the open sea lay to the south and the land to the north. The radiolarian cherts of Devon were doubtless laid down in deep water, the limestones of South Wales in clear water of moderate depth, and the sandstones, shales, and coals of the north in estuaries, deltas, and freshwater basins.

Each seam of coal marks an old land surface; therefore the numerous seams that occur in some regions are an evidence of frequent oscillations of the land.

General uplift and crustal deformation began at the close of the Carboniferous period throughout the Northern Hemisphere, producing the stratigraphical break which separates the Carboniferous from the Permian in Britain and Germany. In the Southern Hemisphere the Carboniferous seems to pass conformably upward into the Permian, from which we are led to assume that the uplift did not affect these regions, thereby permitting deposition to be continuous.

In North America, and generally throughout the Southern Hemisphere, there was pronounced uplift in the Upper Carboniferous, accompanied by continental conditions of deposition over wide tracts.

Subdivision.—In the British Isles the Carboniferous System is divided into three principal groups which may be described as typical of Western and Central Europe, and North America.

	Series.	Rocks.
Upper Carboniferous	4. Coal-Measures.	Sandstones, fireclays, ironstones, and coal-seams.
	3. The Millstone Grit.	Grits, sandstones, shales.
Lower Carboniferous	2. The Yoredale Beds.	Shales.
	1. The Carboniferous (Mountain) Limestone.	Limestones.

Generally speaking, the Lower Carboniferous is everywhere characterised by the marine facies of rocks, and the Upper Carboniferous by the deltaic and terrestrial.

In England the Carboniferous System is mainly developed in Devon, Somerset, South and North Wales, Midlands, and on both flanks of the Pennine Chain.

In Scotland the Carboniferous rocks stretch from south-west to north-east, crossing the country from sea to sea, from Ayr to the Firth of Forth, and occupying the great trough between the slopes of the Grampians and the Southern Uplands.

The Carboniferous of Great Britain was at one time a continuous sheet, but it now occupies a number of disconnected basins that have been produced by two systems of folds, one system, the *Pennine*, running north and south, the other, known as the *Armorican* or *Hercynian*, running from the south of Ireland to Belgium and thence to Central Europe. The Coal-Measures have been preserved in the troughs and removed by denudation from the crests of the folds. Obviously, the preservation of the English coals is due to the depression of the Coal-Measures in troughs that now form disconnected basins.

The Carboniferous rocks in Devon consist of shales with bands of chert, limestone, and seams of impure coal which are locally called *culm*; hence the name *Culm Measures* frequently applied to the whole series. The strata are much folded, and may be divided into two groups of beds corresponding to the Lower and Upper Carboniferous further north.

Carboniferous Limestone.—This is frequently called the Mountain Limestone. It consists of massive limestone that is 1600 feet thick in Derbyshire, and over 2000 feet thick in Ireland, where it occupies more than half of the whole island.

The Mountain Limestone is mainly composed of crinoids, but corals and foraminifera are also plentiful in it in many places. It also contains numerous brachiopods, the most common genera being *Productus*,[1] *Spirifer*,[2] *Athyris*,[3] and *Terebratula*.[4]

The Gasteropods are represented by *Euomphalus* and *Pleurotomaria*; and the Cephalopods by *Orthoceras*, *Nautilus*, and *Goniatites*, the last being very abundant.

The trilobites which appear for the last time in the British Isles are well represented by the genus *Phillipsia*.

When traced northward into Derbyshire, Lancashire, York, and Northumberland, the limestone becomes interbedded with thin bands of shale which increase in thickness going northward and begin to contain thin seams of coal.

In Scotland the Lower Carboniferous consists mainly of red, white, and yellow sandstones, variously coloured shales, limestones and coal-seams, which are the equivalent of the Mountain Limestone of the south. These beds are divided into two groups :—

Lower Carboniferous	2. Calcareous or Carboniferous Limestone Series.	
	1. Calciferous Sandstone Series.	(*a*) Cement Stone Beds. (*b*) Red Sandstone Beds.

The Calciferous Sandstone Series is intercalated with vast sheets of lava and tuffs.

In Ireland the Lower Carboniferous rocks attain their greatest development in the British Isles. They stretch as a continuous sheet from the south coast northward to Donegal Bay and Lough Foyle, and spread eastward to the Irish Sea. Altogether they occupy an area of about 15,000 square miles.

In the south-west they resemble the Culm Series of Devon;

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[1] Lat. *productus* = lengthened.

[2] Lat. *spira* = a coil, and *fero* = I carry.

[3] Gr. *a* = without, and *thyris* = a door.

[4] Lat. *terebratio* = a hole bored.

but in the north the beds show a closer relationship to the Lower Carboniferous of Scotland. In Clare and Galway massive limestones appear with shales at the base and a few lenticular bands of chert, the total thickness of the series amounting to some 3000 feet.

Yoredale Beds.—These succeed the Mountain Limestone conformably and are typically developed in Yoredale, in Yorkshire, where they consist of flagstones, gritstones, shales, and limestones with coal-seams.

This series shows an approach to the estuarine and terrestrial conditions that prevailed in Scotland during the deposition of the Lower Carboniferous Coal-Measures of that region, with which they are perhaps contemporaneous.

The Millstone Grit.—This is a series of beds consisting of massive grits and conglomerates with subordinate bands of shale and impure limestones, some of which contain marine fossils. The grits are mostly composed of angular fragments of quartz and felspar that are probably the waste of the granitic and gneissic areas of North-West Scotland and Norway.

The rocks of the Millstone Grit are frequently current-bedded, which shows that they were deposited by water running in one direction. The presence of the shales, with sometimes marine shells, would lead to the belief that this group of beds was formed in the delta of a large river coming down from the north-east. The fossils are mostly the remains of land plants, but even these are scarce.

Coal-Measures.—These consist of a great succession of shales with subordinate beds of sandstone, impure limestone, ironstone, fireclay, and coal-seams. The original sediments were probably laid down in a great delta or estuary on the southern margin of the great Scandinavian continent.

The shales indicate quiet conditions of deposition, and the numerous seams of coal prove that luxuriant land floras grew on the swampy jungle-like mud-flats bordering the sea. The character and rank growth of the vegetation would point to the prevalence of a warm moist semi-tropical climate.

The coal is mainly composed of the spores, spore-cases, and broken remains of Lycopods, ferns, and horse-tails which accumulated to a great thickness as peat-like sheets on the steaming deltaic mud-flats.

The Lycopods which were allied to the diminutive club-mosses of the present day, grew to the size of forest trees, and their trunks, roots, foliage, and fruit are found associated with the coal. The *Calamites* or horse-tails also grew to a great size; and the ferns and fern-allies flourished in great abundance.

The coal usually rests on a seam of fireclay called *under-clay*, which was the soil in which the coal-vegetation grew, and which became fire-resisting through the exhaustion of the lime and alkalies by the growing vegetation. In these fireclays there are not infrequently found the roots and prostrate trunks of fossil trees. In some places the upright stumps have been found passing into the coal or even reaching into the *roof*, which is usually a stratum of sandstone.

The ironstone found in the Coal-Measures occurs mostly as concretionary lumps embedded in clay. Frequently the concretions are so close together as to form an almost continuous sheet. In each concretion there is usually enclosed a fossil fern-leaf or shell.

The ironstone is mostly carbonate of iron. When associated with clay it is called *clay-band ore*, and when mixed with Carbonaceous matter, *black-band ore.*

The sandstones of the Coal-Measures Series contain many fossil plants, and sometimes thin seams of coal. When highly siliceous they are called *ganister*, which is extensively used as a lining for furnaces.

The Coal-Measures Series contains the productive coal-seams of the English coalfields.

In Scotland there are three productive groups of beds in the Carboniferous System :—

Upper Carboniferous	4. Coal-Measures Series—Upper coal-beds. 3. Millstone Grit Series—Not productive.
Lower Carboniferous	2. Carboniferous Limestome Series—Middle coal-beds. 1. Calciferous Sandstone Series — Lower coal-beds.

The bulk of the productive coal-seams of Scotland belong to the Carboniferous Limestone Series or Middle Coal-beds. Hence we find that the lower coals of Scotland are older than those of England, and we know that this has arisen from the circumstance that terrestrial conditions existed in Scotland during the time that marine conditions prevailed in the South.

Productive coal-seams are not so well developed in the Carboniferous System in Ireland as in England and Scotland.

English Coalfields.—The largest and most productive coalfields in England are as follow :—

1. Bristol.—Coal-Measures 5000 feet thick, with 51 seams of coal, of which 20 are over 2 feet thick.

2. South Wales.—Coal-Measures from 7000 to 10,000 feet thick, with 25 seams over 2 feet thick.
3. North Wales.—Occurs in 2 coalfields—Denbighshire and Flintshire—separated by the great Bala Fault, with a displacement of 10,000 feet.
4. South Staffordshire contains the famous 10-yard Dudley seam.
5. North Staffordshire or Pottery coalfield.—The Coal-Measures are over 5000 feet thick and contain 40 seams of coal.
6. Lancashire.—Coal-Measures, 6000 feet, with 65 seams of coal.
7. Northumberland and Durham.—Coal-Measures about 3000 feet thick, with 15 seams of coal.
8. Yorkshire, Nottingham, and Derbyshire.—Lies east of the Pennine Chain. The southern extension of the Northumberland and Durham coalfield.

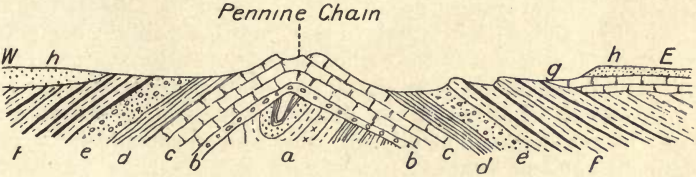


FIG. 216.—Showing section across the Pennine Chain from Lancashire to Yorkshire.

(*a*) Pre-Carboniferous rocks.
(*b*) Basement beds.
(*c*) Carboniferous (Mountain) limestone.
(*d*) Yoredale Shales Series.
(*e*) Millstone Grit Series.
(*f*) Coal-Measures Series.
(*g*) Magnesian limestone—Permian.
(*h*) Permian sandstone.

Coalfields of Scotland.—The principal coalfields in Scotland are as follow :—

1. Clyde Basin.
2. Mid-Lothian, Edinburgh, and Haddington.
3. Fifeshire.
4. Ayrshire.

The Clyde Basin contains the largest and most valuable coalfield in Great Britain. It occupies the greater part of four counties and is traversed throughout its whole length by the Clyde. In Lanarkshire the coal-bearing measures are about 4000 feet thick, and contain fifteen seams of coal and six rich bands of ironstone, much of which is of the black-band variety.

Valuable cannel and oil shales occur west and south of Glasgow and also at Torbane.

Coalfields of Ireland.—The coalfields of Ireland may be divided into northern and southern groups as under :—

Northern Group
1. Leitrim.
2. Connaught and Tyrone.
3. Antrim.

Southern Group
4. Clare, Limerick, and Kerry.
5. Queen's County, Kilkenny.
6. Tipperary.

Denudation has removed the greater portion of the productive Coal-Measures in the north of Ireland.

Contemporaneous Volcanic Rocks.—The early part of the Lower Carboniferous period was disturbed by local volcanic outbursts in the south of Ireland, Devon, Isle of Man, and Derbyshire ; but it was in Scotland that the eruptions attained their greatest intensity. The eruptions began at the close of the Old Red Sandstone period, and, with intervals of rest, continued till the beginning of the Coal-Measures. In the earlier stages the outbursts, according to Sir Archibald Geikie, were characterised by the quiet outpouring of great floods of lavas of the plateau type, and in the waning phases by the emission of piles of ashes and streams of lava from prominent volcanic vents.

The plateau-lavas covered a large area in the Mid-Lothians, and in places reached a thickness of 3000 feet. They are mostly andesitic. The lavas of the volcanic type are mainly basalts.

In Derbyshire the Carboniferous Limestone is associated with sheets of basalt and olivine-dolerite, some of which are apparently contemporaneous, while others are probably intrusive sills.

Beds of volcanic tuff are interstratified with the Lower Carboniferous rocks in the Isle of Man, where intrusive sills, dykes, and agglomerates also occur.

The Carboniferous rocks in Ireland are remarkably free from contemporaneous volcanic outbursts, except at Limerick, where there are two series of volcanic rocks separated by a great thickness of sedimentary rocks. The lower series is mainly composed of andesites and basalts of the plateau type with beds of tuff, and the upper of basaltic lavas.

It is notable that the Carboniferous centres of activity are situated in the same regions as those of the Old Red Sandstone period ; and it is significant that while the rocks of the earlier period in the Midland of Scotland are calcic, those of the Carboniferous in the same region are of a distinctly alkali type.

In the North England coalfields, the Coal-Measures are intruded by many igneous dykes of probably Tertiary date. Some of these dykes, like the well-known Cockfield Dyke of Cleveland, traverse Carboniferous, Permian, Triassic, and Jurassic rocks, and displace the coal-seams like faults.

North America.—The rocks of the Carboniferous System cover an area of approximately 200,000 square miles in the United States and British North America. They are divided into two great sub-systems, comprising eight series, as follow :—

Pennsylvanian (Littoral and lacustrine facies)	8. Monongahela Series — Upper Productive measures.	Coal-Measures.
	7. Conemaugh Series — Barren measures.	
	6. Allegheny Series—Lower Productive measures.	
	5. Pottsville Series— . .	Millstone Grit.
Mississippian (Marine facies)	4. Kaskaskia Series.	Carboniferous Limestone.
	3. St Louis Series.	
	2. Osage or Augusta Series.	
	1. Kinderhook Series.	

The early stages of the Mississippian in Michigan were littoral and terrestrial, but as the result of a general subsidence which affected almost the whole of the Northern Hemisphere, the deposition of the marine facies, mainly characterised by limestones, soon followed.

At the close of the Mississippian, there began a general uplift which led to a return of the terrestrial and continental conditions which characterised the Old Red Sandstone period. During this time of uplift, the Upper Carboniferous Pennsylvanian beds were laid down partly on a sea-littoral and partly in estuaries or enclosed basins. The uplift, as in Europe, continued well into the Permian.

The anthracitic and bituminous coals of Pennsylvania, Illinois, Ohio, and neighbouring States are of vast extent and great value.

India.—In Northern India, in the Spiti Valley, there is a pile of shales 4000 feet thick which is believed to represent the whole of the Carboniferous System. The lower half, known as the *Lipak Series*, is mainly composed of calcareous shales that contain a rich marine fauna, including *Productus*, many molluscs, and the trilobite *Phillipsia*.

The upper half, about 2000 feet thick, called the *Po Series*, consists of quartzites and shales, the lower portion of which contains a few fossil plants that seem to be identical with plants in the *Culm* of Europe and Australia. The upper subdivision contains many marine forms, among which bryozoans are plentiful, including the genus *Fenestella*, which has given its name to this group.

Throughout the whole length of the Himalayas and in the Chinese provinces beyond the eastern limits of India, there is a vast development of volcanic rocks which may perhaps be of Lower Carboniferous age.

The Carboniferous succession in Northern India is as follows :—

Upper Carboniferous—Po Series	(*b*) Fenestella Beds. (*a*) Terrestrial Beds.

Lower Carboniferous—Lipak Series—Marine facies.

It will be seen from this succession that we have in India, at the close of the Lower Carboniferous, the same break as in Northern Europe and North America; which demonstrates that the uplift and crustal disturbance of the northern continents was general throughout the whole of the Northern Hemisphere. The relationship between this uplift and the volcanic activity which disturbed the Lower Carboniferous is not very clear, for it would appear that the volcanic outbursts everywhere preceded the uplift.

Australasia.—Rocks of Carboniferous age occupy extensive tracts in New South Wales, Queensland, Victoria, Western Australia, and Tasmania. In New South Wales the Upper Carboniferous passes upward into the Permian without any evidence of a stratigraphical break. The subdivisions of the Carboniferous recognised in that State are as follow :—

Permo-Carboniferous (11,000 to 13,000 feet)	Sandstones and shales with coal-seams.
Lower Carboniferous (11,000 feet)	Sandstones and conglomerates with bands of shale and limestone.

The Lower Carboniferous rocks occur chiefly between the Hunter and Manning Rivers. The sandstones contain the gigantic club-moss, *Lepidodendron australe*, which is also found in Queensland. It would thus appear that in Eastern Australia the Carboniferous was ushered in with terrestrial conditions of deposition.

The Permo-Carboniferous is the productive coal-series of New South Wales. It is displayed over an area of 25,000 square miles in the Port Macquarie and Newcastle districts. Going southward, the Coal-Measures disappear below the Triassic Hawkesbury Sandstone, and extend along the coast to Sydney, where they have been proved at a depth of 3000 feet below sea-level.

Among the plants associated with the coals are several species of the genus *Glossopteris*, which is characteristic of the Mesozoic Gondwana System of India, and was formerly believed to be confined to the Mesozoic. Its range is now known to extend from the Carboniferous to the Jurassic.

The marine beds of this series contain a rich Carboniferous fauna which includes the brachiopods *Athyris*, *Orthis*, and *Productus*, and the bryozoan *Fenestella plebeia*. The coal occurs in three horizons as determined by Professor David:—

Permo-Carboniferous
- 6. Upper or Newcastle Coal-Measures.
- 5. Dempsey Series.
- 4. Middle or Tomago, or East Maitland Series.
- 3. Upper Marine Series.
- 2. Lower or Greta Coal-Measures.
- 1. Lower Marine Series.

There was intense volcanic activity in the north-east portion of New South Wales, where the Carboniferous strata are intercalated with many sheets of lava, mostly rhyolite, as well as with thick beds of tuff. The Permo-Carboniferous was freer from disturbance, but the strata of this period are intercalated with beds of tuffs and contemporaneous sheets of andesite and basalt.

Associated with the Upper Coal-Measures there are massive beds of conglomerate containing scratched boulders which are believed to have been transported by ice.

In Queensland the Carboniferous rocks have been divided into five distinct series of beds as follow:—

5. Upper Bowen Series—Terrestrial beds with coal-seams and *Glossopteris*.
4. Middle Bowen Series—Partly marine and partly terrestrial, with *Productus* and *Glossopteris*.
3. Lower Bowen Series—Partly terrestrial and partly volcanic.
2. Star Series — Partly freshwater and partly marine, with *Lepidodendron*.
1. Gympie Series—Marine, with *Productus*, *Fenestella*, etc.

The productive Permo-Carboniferous rocks of New South Wales have not been discovered in Victoria, but Lower Carboniferous beds are well developed in Central Gippsland, where they contain characteristic Lower Carboniferous fishes.

The Carboniferous rocks of Western Australia mainly belong to the lower or marine facies. The Permo-Carboniferous type is present in the Irwin and Collie coalfields.

In Tasmania Carboniferous rocks occupy a large tract in the south-east portion of the island. The Lower Carboniferous is typically marine; and the upper Carboniferous, terrestrial or estuarine, consisting mainly of grits and shales with *Gangamopteris*, *Glossopteris*, and *Nœggerathiopsis*. The seams of coal are thin.

Carboniferous rocks of the marine and estuarine types are present in New Zealand, and contain *Productus*, etc.

South Africa.—No Carboniferous rocks have so far been distinguished in South Africa; but it is not improbable that the upper portion of the Cape System may be the equivalent of the European Carboniferous.

Economic Products.—The supreme importance of the Carboniferous System lies in the abundance of coal which it contains. Economically this system is more important than any other, and the value of the coal annually produced from it is greater than the total value of the mineral production of all the other systems put together.

The annual production of coal amounts to about 1,000,000,000 tons, valued at £500,000,000, which exceeds the value of the annual output of iron, gold, silver, tin, copper, lead, diamonds, and all other minerals more than twofold.

The ironstones produced from the Coal-Measures of Great Britain and Western Europe are still of great value.

The limestones of this system are useful as building-stone and for the production of lime for mortar and agricultural purposes.

CHAPTER XXVII.

PERMIAN SYSTEM.

THE Permian is the youngest of the Palæozoic systems. In Southern Europe, Russia, India, Australia, and South Africa, it follows the Carboniferous quite conformably; but in the British Isles and Germany it is separated from the Carboniferous by a well-marked physical break, and in these regions is more closely related to the Mesozoic than to the underlying Palæozoic formations.

In Europe the series of red sandstones, marls, conglomerates, breccias, limestones, and dolomites which follows the Carboniferous was formerly known in England as the *New Red Sandstone* to distinguish it from the *Old Red Sandstone* which underlies the Carboniferous.

The lower portion of the New Red Sandstone was subsequently found to contain fossils related to those in the Carboniferous, and the upper portion fossils related to Mesozoic forms. This led to the division of the New Red Sandstone into two distinct systems, the lower, called the Permian System, being placed in the Palæozoic; and the upper, called the Triassic System, being referred in the Mesozoic.

The name Permian was first suggested by Sir Roderick Murchison in 1841 for a great development of these rocks in the old kingdom of Perm in Eastern Russia.

The Permian System of England is the *Dyas* of German geologists.

Distribution.—The Permian System attains a considerable development in Russia, Germany, France, Alps, Sicily, Armenia, India, Australia, South Africa, and South America. The area it covers in the British Isles is comparatively insignificant.

Rocks.—In Europe the Permian consists of two distinct facies of rocks, namely, the *Dyas* type of Germany, and the *Russian* type.

In the Dyas type there are, as the name implies, two divisions or groups of beds: (1) a lower terrestrial series consisting mainly of red sandstones and conglomerates; and (2) an upper marine series of limestones and dolomites.

In the Russian type the same strata are represented, but they are interstratified in such a way as to preclude a twofold subdivision; that is, there is an alternation of terrestrial and marine beds throughout the whole system.

The prevailing rocks of the European Permian are red sandstones, in many places interbedded with bands of conglomerate, fine shales, or marls. The basal beds are frequently conglomerates, which in places pass into coarse angular breccias.

The sandstones are typically brick-red, and the so-called marls are even deeper red. In many parts of Germany the marl-slate is impregnated with a small percentage of copper-ore.

The limestone, which may be regarded as characteristic of the Dyas type, is well bedded, often clayey, and usually more or less dolomitic.

On the flanks of the Harz Mountains the sandstones contain seams of coal with which are associated bituminous shales and ironstones.

In Western Europe the lower portion of the Permian is intercalated with masses of contemporaneous igneous rocks.

Relationship to Carboniferous.—Throughout Western and Central Europe the Permian rests on the denuded folds of the Carboniferous System and on older rocks. Obviously the folding and denudation took place after the deposition of the Carboniferous and before the Permian period began. In the interval that separates these two systems the greater portion of Northern Europe must have been dry land.

But in portions of North America, Eastern and Southern Europe, Central Asia, and Australia, the Carboniferous seas still existed, and on the floor of these there was laid down a continuous succession of marine sediments, covering the interval which separates the Carboniferous and Permian in Western and Central Europe. That is, the interval representing the unconformity in Europe is bridged over by what may be described as *transition beds*. Therefore, in the regions where a continuous sea existed throughout the Upper Palæozoic, we get the following succession:—

$$\text{Upper Palæozoic}\begin{cases}\text{Permian.}\\ \text{Permo-Carboniferous (Transition Beds).}\\ \text{Carboniferous.}\end{cases}$$

Conditions of Deposition.—The distribution and character of the Permian in Europe afford conclusive proof that the great Scandinavian continent of North-West Europe, which played so important a rôle in the formation of the Carboniferous Coal-Measures of Western Europe, gradually increased in size until its shores encroached on Southern Europe. The late Carboniferous uplift of the northern lands, with the simultaneous retreat of the sea to the south, was merely an expression of a great crustal disturbance which affected a wide zone of country which can be traced from the southern extremity of Ireland eastward through the southern promontories of South Wales and Mendip Hills to Belgium and Central Germany. This belt of intense folding everywhere followed an approximate WNW.–ESE. course, and raised a system of mountain folds, known as the *Armorican* or *Hercynian* Chain, which extended from the Atlantic eastward to Central Europe, but of which only the worn-down stumps now remain, mostly buried beneath the later rock-formations.

The name *Armorican* is derived from Armorica, the ancient name of Brittany, where the chain attained a great height; and the name *Hercynian* from the Hercynian Forest, of which portions still remain in Swabia and the Harz Mountains.

The productive coal-basins of Ireland, Great Britain, North France, and Belgium lie in the northern folds of the Armorican Chain.

The general uplift we have spoken of caused the sea to retreat southward, and at the same time it established continental conditions in Northern Europe, where great inland basins of the Caspian type and seas of the Mediterranean type were formed. In these Permian basins and land-locked seas, to some of which the ocean still had access, was laid down a great succession of sandy, pebbly, and clayey deposits, alternating with calcareous sediments. Some of the sandstones present the aspect of consolidated sands that may have accumulated in desert conditions not unlike those prevailing at the Isthmus of Suez, where we have a tract of more than 10,000 square miles of wind-blown desert sand, salt-water lagoon, and swamp, lying a few yards above sea-level.

In the land-locked basins the fauna was meagrely represented by forms descended from the inhabitants of the Carboniferous seas. Amphibians crawled about the marshy shores, and the land supported a vegetation closely related to the Carboniferous.

Fauna.—The conditions of life and the environment that prevailed in Northern Europe were not favourable for the development of a prolific fauna. The majority of the Carboniferous genera disappeared before the continental conditions became general, and the forms that survived were mostly small and frequently of abnormal type. Moreover, the increasing salinity of the enclosed basins was not favourable for the introduction of new genera.

The forms that were least affected by the changed conditions were the Polyzoans, which flourished in such abundance as to constitute the bulk of the limestones.

Among the Polyzoans *Fenestella retiformis* is a characteristic species.

The corals, echinoderms, and Cephalopods that were so prominent in the Carboniferous seas have almost disappeared. Trilobites are unknown in the British Permian, and are but feebly represented elsewhere.

Generally the fauna of the lower division of the Permian possesses a terrestrial facies, and consists of insects, molluscs, crustaceans, a few fish, and amphibians, the last represented by Labyrinthodonts.

In the limestones and dolomites of the Upper Permian are found a few stunted brachiopods, Lamellibranchs, Gasteropods, and Cephalopods.

While the fauna entrapped in the Caspian-like seas show unmistakable evidence of decadence, the genera living in the open seas continued to flourish and follow the normal processes of development. In Sicily, Armenia, and India there lived a rich and varied marine fauna, in which new genera came in to take the place of the old.

The normal marine Permian fauna is therefore not found in Western or Central Europe, but in Southern Europe and Asia, where it is represented by corals, bryozoans, brachiopods, and numerous molluscs.

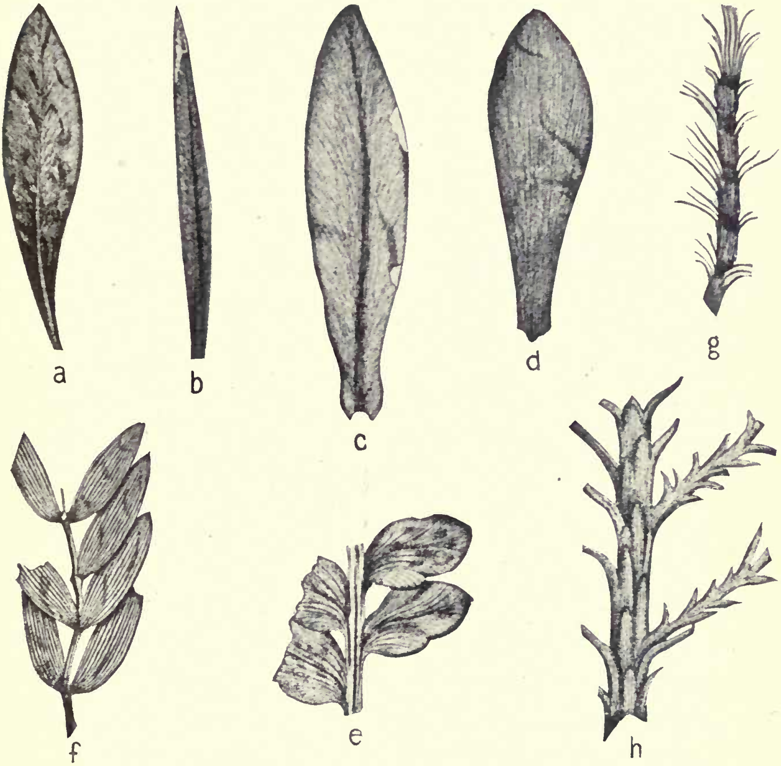
Ammonites, which are so characteristic of the Mesozoic formations, began to appear for the first time in the Permian seas; and the earliest reptiles, represented by the genera *Proterosaurus* and *Palæohatteria*, are present in the continental Permian of Germany.

The Brachiopods include *Productus*, *Spirifer*, *Spiriferina*, *Terebratula*, and *Rhynchonella*; the Gasteropods, *Bellerophon*, *Pleurotomaria*, and *Naticopsis*; the Lamellibranchs, *Avicula*, *Pecten*, *Schizodus* (allied to *Trigonia*); and the Cephalopods, the ammonoids *Medlicottia* and *Popanoceras*, and a whole series of Orthoceratites.

Plants are represented by many survivors from the Carboniferous, and include the familiar *Calamites*, also *Walchia* (Plate XXXVIII. fig. 2) and *Callipteris*.

In America, as in Europe, the close of the Carboniferous witnessed great changes in the distribution of the land. Freshwater deposits continued to be laid down in the Coal-Measure basins in Pennsylvania, Ohio, West Virginia, and Maryland; and a vast sheet of Permian of the Mediterranean type of deposits was laid down in Texas, Kansas, and Nebraska.

The dominant feature of the Southern Hemisphere in this period is a vast pile of shales and sandstones of a deltaic and terrestrial facies, comprising what is typically known in India as the *Gondwana System*, which ranges in age from the Permo-Carboniferous



REPRESENTATIVE TYPES OF GLOSSOPTERIS FLORA.

(*a*) *Glossopteris communis.*	(*e*) *Neuropteris valida.*
(*b*) *G. angustifolia.*	(*f*) *Schizoneura gondwanensis.*
(*c*) *Gangamopteris cyclopteroides.*	(*g*) *Phyllotheca indica.*
(*d*) *Nœggerathiopsis hislop.*	(*h*) *Voltzia heterophylla.*

(After Chamberlin and Salisbury.)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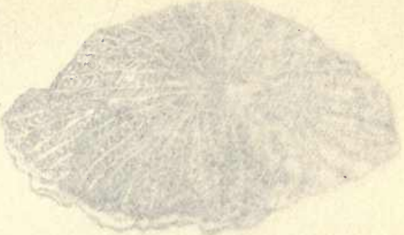
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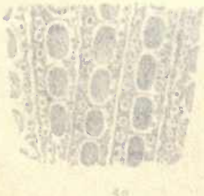
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PERMIAN FOSSILS.

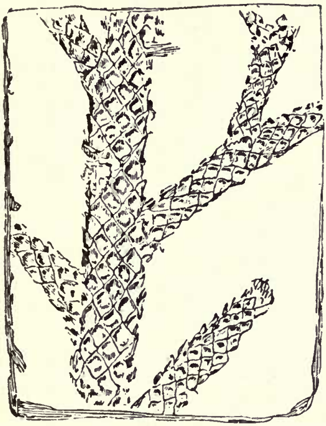
PLATE XXXVIII.

PERMIAN FOSSILS.

1. *Voltzia heterophylla*. Permian.
2. *Walchia Schlotheimii*. Permian.
3. *Synocladia virgulacea* (Phill.). Permian. Humbleton, Tunstall, etc.
4. *Fenestella retiformis* (Schloth.). Permian. Tynemouth, Humbleton, etc.

4*a*. Enlarged portion of *Fenestella retiformis*. Permian. Humbleton, etc.

5. *Productus horridus* (Sow.). Permian. Humbleton, Tunstall, Tynemouth, etc.
6. *Strophalosia Morrisiana* (King). Permian. Tynemouth, Humbleton, etc.



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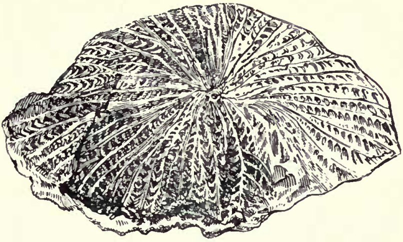

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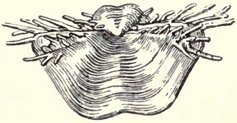

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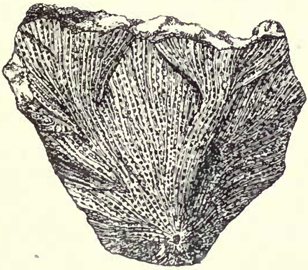

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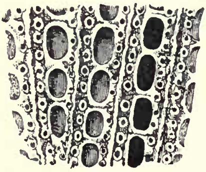

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PERMIAN FOSSILS.

to the Jurassic. This system is well developed in Australia, New Zealand, South America, South Africa, and Antarctic continent; and is everywhere characterised by the presence of a peculiar terrestrial vegetation usually called the *Glossopteris* flora (Plate XXXVII.). The most distinctive types of this are the ferns *Glossopteris* and *Gangamopteris*, and the horse-tail *Schizoneura* (Plate XXXVII.).

The wide distribution of the *Glossopteris* flora in India, Australia, South Africa, and South America has given rise to the belief that the sediments, in which the remains of this flora are preserved, were laid down on the margin of a great continent which occupied the site of the existing Indian Ocean, and extended in the Australian and American quadrants to the Antarctic region. The ancient continent has been called *Gondwana Land.* It attained its greatest size and height at the close of the Carboniferous period, and existed till near the close of the Mesozoic era.

The existence of an almost identical flora in regions so far apart would tend to show that the climatic conditions prevailing around the littoral of Gondwana Land were everywhere about the same. The great thickness of water-borne sediments, the Alpine glaciation, and the dense deltaic jungle vegetation whose buried remains now form valuable seams of coal, all bear evidence of an abundant rainfall and temperate coastal climate.

British Isles.—A considerable development of Permian rocks occurs in England on both sides of the Pennine Chain, in the Midlands, and in Devon. In Scotland small areas of Permian strata are found in Ayrshire, Dumfriesshire, and Isle of Arran; and in Ireland a few small patches crop out in County Tyrone, and on the south shore of Belfast Lough.

The subdivision of the Permian, as it occurs on the Yorkshire side of the Pennines, is as follows :—

Upper Permian	4. Red Sandstone and Marl. 3. Magnesian Limestone.
Lower Permian	2. Marl-slate. 1. Yellow Sands.

The Magnesian Limestone is the most conspicuous member of the succession. In Durham it is over 600 feet thick.

On the Lancashire side of the Pennine Chain the Magnesian Limestone is subordinate in extent; and the place of the Yellow Sands is taken by sandstones, with which are associated breccias and conglomerates, the total thickness of this basal series in places being 1500 feet.

The breccias were at one time believed to be of glacial origin, but the present view is that they are ancient screes of frost-shattered rock that descended into the Permian basins.

Germany.—The Dyas type of the Permian System is well developed in the Rhine Province, Thuringia, Saxony, Bavaria, and Bohemia. It is typically displayed in the flanks of the Harz Mountains.

The two great divisions of the Dyas are :—

2. Zechstein [1]—Limestones and clayey beds.
1. Rothliegende [2]—Red sandstones and pebbly beds.

These two divisions are quite distinct, and on account of overlap arising from subsidence, the *Zechstein* is found covering regions far beyond the limits of the underlying *Rothliegende.*

The copper-bearing shales at Mansfeld, on the south flank of the Harz Mountains in Upper Saxony, have been famous as a source of copper for many centuries. They occur at the base of the Zechstein.

Russia.—Rocks of Permian age cover an enormous tract in Eastern Russia, principally in the province of Perm, which is bounded on the east by the Ural Mountains. They follow the Carboniferous conformably, and consist of sandstones, marls, shales, conglomerates, and limestones, the latter usually dolomitic. Intercalated with these rocks there are beds of rock-salt, gypsum, and thin seams of coal.

The terrestrial beds at the base contain many land plants, including *Calamites* and *Pecopteris,* also fish and labyrinthodont remains. The limestone bands are marine, and contain several brachiopods, among which *Productus* is represented by a few species.

The Russian type of Permian is also found in Armenia.

India.—In the Salt Range of the Punjab the Permian *Damuda* Series attains a thickness of about 10,000 feet, and contains, among other plants, the genera *Glossopteris, Gangamopteris,* and *Schizoneura.*

The coarse *Talchir* conglomerates at the base of the Permo-Jurassic Gondwana System contain striated and smoothed boulders which are believed to be of glacial origin.

South Africa.—At the base of the Permo-Jurassic Karoo System, which occupies a prominent place in the geological structure of South Africa, there occurs a series of shales and conglomerates called the *Dwyka* Series.

The Dwyka conglomerate of this series contains striated stones and boulders that are now generally believed to be glacial.

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[1] Zechstein = *solid or tough rock,* referring to the character of the limestone.

[2] Rothliegende = *red-dead-layer,* referring to the sudden disappearance of the copper in passing downward into the sandstones of this group.

This remarkable conglomerate occupies an extensive tract in North and South Cape Colony, Orange River State, and the Transvaal, where it forms an encircling sheet around the margin of the Karoo Basin. In the south it is about 1000 feet thick, but going northward it diminishes in thickness. It is devoid of all organic remains except at Vereeniging, where the overlying shales contain the remains of many varieties of plants and coal-seams.

The subdivisions of the Dwyka Series are as follow :—

Dwyka Series	3. Upper Shales . . .	600 feet.
	2. Dwyka Conglomerate .	1000 ,,
	1. Lower Shales . . .	700 ,,

North America.—The older Permian beds in the State of Kansas are marine. They are followed by sandstones containing beds of gypsum and salt, which would indicate that the Permian uplift enclosed salt-water basins in an arid region where the evaporation was greater than the precipitation.

The subdivision of the Permian in Kansas, where the development of the system may be taken as typical, is as follows :—

Permian	4. Kiger Stage	Cimarron Series.
	3. Salt Lake Stage	
	2. Summer Stage	Big Blue Series.
	1. Chase Stage	

In Texas, where the development of the Permian System is greater than in any other State, the strata attain a thickness of 7000 feet.

Permian Glaciation.—Notable evidences of Permian glaciation are found in South Africa, where the famous Dwyka Conglomerate, lying near the base of the Karoo System, contains striated boulders, and possesses many of the characteristics of a consolidated glacial till ; hence the name *tillite* which has been applied to it by Davis. In some places it rests on a striated platform of older quartzite.

In Victoria the well-known Upper Carboniferous or Permian glacial deposits at Bacchus Marsh, Bendigo, and other places, contain smoothed and striated boulders, and rest on striated, grooved, ice-worn surfaces.

The Bacchus Marsh glacial conglomerate is believed by some writers to occupy a position equivalent to the Talchir glacial conglomerate at the base of the Indian Gondwana System.

The Lyons Glacial Conglomerate in Western Australia has been shown by Gibb Maitland to be associated with strata containing a marine fauna which seems to fix its age as Permo-Carboniferous. It can be traced without a break in a NNW.–SSE. course from latitude 23° south to latitude 26° south.

Glacial conglomerates are associated with rocks of Permo-Carboniferous age in many parts of South America, typically in Brazil and Argentina. Near Minas, Brazil, in latitude 28° 30′ south, there is a glacial boulder-bed known as the *Orleans Conglomerate* lying below beds containing *Glossopteris* and *Gangamopteris*.

Near San Luis in Argentina a similar glacial conglomerate is associated with strata containing *Glossopteris*.

The whole of the southern portion of East Falkland Island is composed of Permo-Carboniferous strata characterised by the typical *Glossopteris* flora; and beneath these there is a clayey bed containing boulders and blocks of apparently glacial origin.

A coarse conglomerate containing many large angular blocks of granite occurs at the base of the Permo-Jurassic Hokonui System of New Zealand, and is believed to be of fluvio-glacial origin.

There appears to be overwhelming evidence of widespread Permian glaciation in India, Eastern Australia, South Africa, and South America, in regions both north and south of the equator, that now enjoy tropical and semi-tropical climates.

It is almost certain that the uplift which began in the Carboniferous culminated in the early stages of the Permian; and we are led to the belief that the glaciation of that period was essentially of the Alpine type.

In India, Gondwana glacial beds occur in the Talchir district and the Salt Range, at places from 700 to 800 miles apart. In Australia, the glacial conglomerates have been traced through 20 degrees of latitude; while in South Africa the Dwyka Conglomerate has a horizontal range of 800 miles. These are significant facts, and seem to support the view that the Gondwana continent was traversed by gigantic ice-covered Alpine chains. The widespread glaciation of the regions bordering this ancient land is one of the most interesting features of the Permo-Carboniferous period in the Southern Hemisphere.

It is not improbable that the height of the mountain-chains and the amount of precipitation were sufficient to favour the accumulation of great valley-glaciers that descended to the foothills, where they deployed as wide piedmont sheets of ice on the shores of the inland basins and land-locked seas.

Economic Products.—Rocks of Permian age produce vast quantities of rock-salt and gypsum, and also some copper.

The German Zechstein or Upper Permian is celebrated for its extensive beds of rock-salt which occur on the north of the Harz Mountains. The rock-salt at Strassfurt in Prussia is 1200 feet thick, and is followed by a zone 150 feet thick of potassium and magnesium salts. At Sperenberg, south of Berlin, the bed of salt is 1100 feet thick.

Photo. by E. F. Pittman.] [*Lent by Geo. Survey of New South Wales.*

DOLERITE DYKE INTERSECTING THE PERMO-CARBONIFEROUS COAL-MEASURES, NOBBYS, NEWCASTLE, N.S.W.

The course of the dyke can be seen in the foreground, together with some masses of coal which have been cindered by the heat of the intrusive lava.

The beds of rock-salt and gypsum in Kansas are of great extent and value.

The copper-bearing shales at Mansfeld, in Saxony, have been a source of copper for many centuries. At Kokand, in Turkestan, the Permian sandstones contain about one per cent. of copper in certain zones.

CHAPTER XXVIII.

MESOZOIC ERA: TRIASSIC SYSTEM.

THE Mesozoic era comprises that portion of the geological record lying between the Palæozoic and Cainozoic eras, and its deposits contain a fauna and flora that form the connecting-link between the ancient and existing life; hence the origin of the name, which signifies *middle life*.

The sedimentary rocks of this era are usually divided into three great systems, namely:—

3. Cretaceous.
2. Jurassic.
1. Triassic.

In Northern India, South Africa, and Australia there is a continuous conformable succession of strata ranging from the Permian to the Jurassic. In England and Eastern States of North America the Trias rests unconformably on the Permian, and in other regions there are breaks in the Mesozoic succession arising from warping and differential crustal movements.

The dominant rocks of the Mesozoic formations are sandstones, shales, and conglomerates of the continental facies, with which are often associated lenticular beds of rock-salt and gypsum, and limestones and marls of the marine facies. The limestones are usually more or less dolomitic.

Generally speaking, the Mesozoic rocks are (1) more calcareous than the Palæozoic; (2) less metamorphosed; and (3) less disturbed, except where they have been entangled in the folds of mountain-chains.

As they have suffered less metamorphism, such altered rocks as slates, schists, and quartzites are relatively scarce, and seldom or never seen except in regions of intense folding and tectonic disturbance.

Mesozoic rocks take a prominent place in the geological structure of the Pyrenees, Alps, Apennines, Carpathians, Urals, Himalayas, New Zealand Alps, Andes, Sierras, Rocky Mountains, and all the great mountain-chains of the globe, the age of which is therefore post-Mesozoic.

The Mesozoic formations are frequently invaded by igneous dykes and intrusive sills of Tertiary date, but except in a few isolated places of limited extent they are singularly free from intercalations of contemporaneous volcanic rocks until the close of the Cretaceous, from which it would appear that the Mesozoic era enjoyed almost complete immunity from volcanic activity throughout the whole globe.

The close of the Carboniferous period, as previously described, witnessed widespread crustal movements and uplift, which eventually led to the continental conditions of deposition so characteristic of the Permian. The continental conditions that prevailed in Western and Central Europe and other regions during the early Mesozoic were merely a continuance of the Permian conditions.

But although there is no evidence of contemporaneous folding, volcanic activity, or intense disturbance of any kind until the closing stages of the Mesozoic, the character of the sediments prove conclusively that there were minor oscillations of the land, and that in the Northern Hemisphere there was a general downward movement which culminated in the Jurassic.

In the Mesozoic there was a marked decline of the brachiopods. The graptolites, trilobites, armoured fishes, *Lepidodendron*, and *Calamites* which characterise the Palæozoic era, are entirely absent. On the other hand, there is a great development of Saurians, Ammonites, and Belemnites. But the feature which specially characterises the Mesozoic is the appearance of the earliest birds, mammals, leaved trees, and flowering plants.

The life of the Lower Mesozoic is related to that of the Palæozoic, and of the Upper Mesozoic to that of the Cainozoic.

Triassic System.

The Triassic is the oldest of the Mesozoic systems, and it owes its name to the three groups or series into which it is divided in Germany, where it is typically developed, and where it was first studied in detail.

Rocks and Distribution.—Throughout the globe there are two dominant facies of Triassic deposits, the *Continental* and *Marine*, each occupying a well-defined geographical province.

In Europe, where the two facies of the Trias was first recognised, the Continental facies, which is mainly developed in the great Germanic Basin of Central Europe, is called the *German*; and the Marine facies, which is typically developed in the Maritime Alps, the *Alpine.*

The *Continental* Trias consists mainly of red sandstones, shales, and conglomerates, with beds of rock-salt and gypsum.

The *Alpine* Trias is mainly composed of thick masses of marine limestone, with beds of marls and shales containing marine shells.

The fossil remains found in the rocks of the German facies are chiefly those of land plants and land animals. The sandy beds frequently exhibit current-bedding, are often ripple-marked, sun-cracked, and imprinted with the tracks of land animals. These features, when taken in conjunction with the prevailing red colour of the sediments and the intercalated beds of gypsum and rock-salt, seem to show that the rocks of this facies of the Trias originated in continental conditions, perhaps not unlike those now prevailing in the Caspian Basin, where the deposits are partly desert sands and partly fluvio-lacustrine.

The inland basins in which these continental deposits accumulated were probably situated in maritime regions where slight oscillations of the land permitted occasional invasions of the sea.

The meagre land flora, the scanty fauna and the existence of the beds of gypsum and rock-salt indicate the prevalence of arid climatic conditions in a wide zone passing through Western and Central Europe. Desert conditions also prevailed in the Eastern States and Western Interior Basin of North America.

The fluvio-lacustrine or continental Trias of South Africa, with its numerous carnivorous and herbivorous saurians and amphibians, and the complete absence of intercalated deposits of rock-salt and gypsum, clearly points to the prevalence of luxuriant jungle conditions somewhat similar to those now prevailing in the great lake-basins at the sources of the Nile.

The *German* Trias is extensively developed in Germany, where it occupies a larger area than any other formation. It also occurs in North-East Russia, in the British Isles, in the Eastern States, and Interior Basin of North America.

The Alpine Trias, which is believed to be the time-equivalent of the Continental facies, is extensively developed in Southern Europe, Asia Minor, Northern India, South-East Asia, New Zealand, Peru, Mexico, and Western States of North America.

GERMAN OR CONTINENTAL FACIES.

Subdivisions in Germany.—There are three main divisions of the Trias recognised in Germany, namely :—

3. Keuper—Red sandstones, conglomerates, and shales.
2. Muschelkalk—Massive dolomitic limestones.

1. Bunter—Red sandstones, conglomerates, and shales, with beds of gypsum and rock-salt.

The Bunter Series.—This series was deposited partly in inland seas and partly on the dry land as wind-blown sands. The sandstones are frequently current-bedded, and the tracks of land reptiles are sometimes found in both the shales and sandstones, which tends to show that they were deposited in shallow bays, estuaries, or deltas. In many cases the tracks occur in muddy sediments that are sun-cracked, which would indicate tidal conditions of deposition, or the existence of marshy swamps subject to occasional inundations. The prevailing colour of the rocks is red, which is characteristic of desert sands that have been subject to the oxidising influence of the atmosphere.

The Bunter Sandstone, as this series is frequently called, follows the Permian quite conformably.

Among the few fossils found in the lower part of the series are the characteristic Triassic species *Estheria minuta*, a diminutive crustacean, and *Gervillia Murchisoni*. About the middle of the series the sandstones contain the footprints of the amphibian *Cheirotherium* and the remains of the Labyrinthodont, *Trematosaurus Brauni*.

In the upper part of the series the sandstones are in some regions, notably in Thuringia, intercalated with mud-beds of dolomitic limestone containing many fossils, among which is the characteristic Lamellibranch, *Myophoria costata*. Other common forms are *Myophoria vulgaris*, *Gervillia socialis*, *Pecten discites*, and *Lingula tenuissima*, all found in the overlying Muschelkalk.

The fine-grained micaceous sandstones of the Eifel contain numerous plant remains, among which occur the peculiar conifer *Voltzia* of world-wide distribution, and a species of *Equisetum*.

The Muschelkalk Series.—This attains a maximum thickness of 1000 feet, and is mainly calcareous and marine. It follows the Bunter Sandstone quite conformably, and its presence is an evidence of subsidence followed by the trespass of the sea into the Bunter basins, which were obviously situated in maritime regions.

The lower and upper portions of the Muschelkalk consist of thin bedded limestones and marls, and the middle portion, of dolomites with beds of gypsum and salt-bearing marls.

The series contains many bands that are richly fossiliferous. The lower beds contain numerous fine examples of *Natica gregaria* and *Dentalium torquatum*; and these are followed by beds crowded with *Myophoria orbicularis*. Among other common forms in the Lower Muschelkalk are *Terebratula vulgaris*, *Athyris trigonella*, *Spiriferina gracilis*, *Myophoria vulgaris*, *M. elegans*, *Gervillia* *costata*, *Monotis Alberti*, *Lima lineata*, *Pecten discites*, and many Ammonites.

The Upper Muschelkalk is the most prolific in fossils, and among the species that occur in vast numbers are *Terebratula vulgaris*, *Myophoria vulgaris*, *Pecten discites*, *Gervillia socialis*, and *Encrinus liliiformis*. The large Nautilus *N. bidorsatus* is common, as also are the brachiopods *Spiriferina*, *Athyris*, and *Terebratula*.

The Keuper Series.—This consists of various coloured clays, mostly red, and sandstones, which contain thick beds of gypsum and thin beds of rock-salt. Fossils occur in all the divisions of the series, but are never abundant.

The general character of the rocks and fossils show that the Keuper sediments were laid down in shallow estuaries or continental basins to which the sea had occasional access.

The estuarine conditions of the Lower Keuper are characterised by the presence of *Myophoria Goldfussi*, *M. costata*, *Lingula tenuissima*, *Estheria minuta*, and the fishes *Acrodus*, *Hybodus*, and *Ceratodus*; and the terrestrial conditions by amphibians and saurians, the latter including the genera *Mastodonsaurus* and *Nothosaurus*. Plant remains are also common.

The Middle or Main Keuper is a group of gypsum-bearing shales and marls, which passes upward into sandstones with *Equisetum arenaceum*. Still higher is the famous Stuben Sandstone which, near Stuttgart, has yielded numerous saurian remains, including those of the crocodile *Belodon*, which is also found at Elgin in Scotland.

The Upper Keuper, or Rhætic as it is sometimes called from its occurrence in the Rhætian Alps, contains the characteristic species *Avicula contorta*, which is limited to this stage and is therefore of zonal value. Among other forms that occur in these beds are *Modiola minuta* and *Protocardia Rhœtica*, but they are nowhere abundant. The coal-bearing sandstones of this stage contain the remains of many cycads, ferns, and horse-tails.

The Upper Keuper is also celebrated for its *Bone-bed*, from which, near Stuttgart, were obtained the teeth of the small marsupial-like quadruped *Microlestes antiquus*, which is the oldest known mammal. The remains of this mammal have since been found in England and United States.

Great Britain.

In England Triassic rocks are present in Devon, whence they extend into Somerset, South Wales, and the Midlands, where they spread out considerably and divide into two main arms that extend northwards, one passing on one side and the other on the other side of the Pennine Chain like the prongs of a hay-fork.

The Trias of England belongs to the *German* or Continental facies, and closely resembles the rocks and succession in Central Germany with one important exception. The Muschelkalk limestone series which so completely dominates the Middle Trias of Central Europe is entirely absent.

The Keuper follows the Bunter series in England with little or no stratigraphical break, and hence we may assume that, while the Muschelkalk was being deposited in Germany, deposits of a Continental facies continued to be deposited in England due to a continuance of the continental conditions which prevailed in the Bunter period. The German Muschelkalk may possibly be represented in England by beds that now form a part of the Keuper and Bunter in that region. If this view be correct, then we must conclude that the subsidence which permitted 1000 feet of marine beds to be deposited in Germany did not affect the British Isles.

The three main divisions of the Trias recognised in the British Isles are :—

3. Rhætic—Maximum thickness, 150 feet.
2. Keuper— ,, ,, 3000 ,,
1. Bunter— ,, ,, 2000 ,,

The **Bunter** consists of red and variously hued sandstones and conglomerates or pebble beds of fluviatile or fluvio-lacustrine origin. The fossils comprise the remains of land plants, among which are the cypress-like conifers *Voltzia* and *Walchia*.

The **Keuper** consists mainly of marls and sandstones; but north of the Mendip Hills it has a remarkable littoral conglomerate at its base from 150 to 250 feet thick, chiefly composed of pebbles of Carboniferous limestone ranging from a few inches to three feet in diameter, set in a dolomitic limestone matrix. Hence the name *Dolomitic Conglomerate*. This conglomerate is quite local in distribution, and is obviously a shore deposit formed at the foot of a steep range rising abruptly from the shore of an enclosed sea.

All through the south-west of England the Keuper beds overlap the Bunter; and even the Lower Keuper is overlapped by the Upper Keuper, which is conclusive evidence of subsidence accompanied by a fairly rapid advance of the waters of the inland basin. Such conspicuous overlap as may be seen on the Welsh borders could only have taken place where the land fringing the basin of deposition sloped gently down to the edge of the water.

The **Rhætic** of England forms the summit of the Keuper in Germany, where it is not recognised as a separate series. It is of marine origin; although relatively thin, it is widespread and forms the closing stage of both the German and Alpine Trias throughout Western, Central, and Southern Europe. From this we learn that the general subsidence which took place in Continental Europe at the close of the Trias also affected the British Isles; and the conspicuous overlap of the different beds of the Keuper, to which we have referred above, shows that the downward movement commenced in early Triassic times. This subsidence eventually led to the introduction of marine conditions of deposition in the English area.

The Rhætic in a way comprises *passage-beds* connecting the Triassic and Jurassic systems. It is characterised in England, as also in Germany, Southern Europe, Indo-China, and Shan States, by the presence of *Avicula* (*Pteria*) *contorta*, which was first described by Portlock from examples found near Port Rush, in Ireland.

Among other fossils found in the English Rhætic are *Protocardia rhætica* and *Estheria minuta*, both of world-wide distribution. At the base of the Rhætic there is a bone-bed which has yielded the teeth of a small mammal, which has been referred to the genus *Microlestes*.

A small patch of Triassic sandstone near Elgin, in Scotland, has been a prolific source of saurian remains. Among the genera found there are *Gardonia*, *Elinia*, *Hyperodapedon*, and many others.

ALPINE TRIAS.

Triassic formations of the Alpine or Marine facies are widely distributed in Southern Europe, particularly in the Maritime Alps, Apennines, Sicily, Balearic Isles, Spain, Balkan Peninsula, Carpathians; and in Turkestan, Central Asia, Northern India, Burma, Japan, Northern Siberia, Spitzbergen, New Guinea, Australia, New Zealand, South Africa, Peru, Mexico, California, Nevada, British Columbia, and Alaska.

The Alpine Trias is typically developed in the Maritime Alps, where Mojsisovics has recognised five divisions or groups of beds :—

5. Rhætic.
4. Carinthian.
3. Norian.
2. Alpine Muschelkalk.
1. Alpine Bunter Sandstone.

The **Alpine Bunter Sandstone** consists of a series of red sandy micaceous slates containing beds of gypsum and rock-salt in the lower stages, and bands of impure limestone in the upper.

The series is quite conformable to the Permian, and hence it is difficult to fix the boundary between the two. The typical fossils are *Avicula Clarai*, *Naticella costata*, and *Ceratites cassianus*, with *Myophoria costata* in the upper calcareous layers.

The **Alpine Muschelkalk** consists mainly of limestones with clayey-bands that contain an abundance of marine fossils, among which Brachiopods are conspicuous, including *Athyris trigonella*, *Spiriferina Mentzeli*, and *Terebratula vulgaris*. Other abundant forms are *Gervillia socialis*, *Myophoria vulgaris*, *Pecten discites*, and *Encrinus liliiformis*. The Ammonites *Ceratites*, *Arcestes*, and *Pinacoceras* are common.

The massive bands of limestone are believed to be old coral reefs.

The **Norian Series** comprises rocks laid down in two distinct biological provinces, one called the *Juvavian Province*, reaching eastwards from Salzburg to the Carpathians; the other, known as the *Mediterranean Province*, comprising the remainder of the Alpine region.

Each province is characterised by its own fauna, and singularly enough the numerous Ammonites of these two adjacent marine areas belong to different species, showing that each province had its own peculiar biological development.

The *Mediterranean Province* is typically developed in the Southern Tyrol, where the rocks consist of massive dolomitic limestones and marly sandstones, the former probably of old coral reef formation. In the Bavarian Alps the dolomites are mainly composed of rock-building marine algæ. The distinguishing fossils of this province are the characteristic Ammonite *Trachyoceras Archelaus* and the Lamellibranch *Daonella* (*Halobia*) *Lommeli* (Plate XXXVIIIb. fig. 2), which has a world-wide distribution, being abundant even in the Trias of New Zealand.

The *Juvavian Province* consists mainly of massive dolomitic limestones and marly beds containing a rich fauna, which includes the Cephalopods *Pinacoceras*, *Arcestes*, *Trachyoceras*, *Nautilus*, and *Orthoceras dubium*; also the Lamellibranchs *Halobia* and *Monotis salinaria*, the last abundant in the Alpine Trias of Siberia, Japan, Australia, New Zealand, North and South America.

The **Carinthian Series** consists chiefly of coral limestones and calcareous marls, the latter best known as the *St Cassian Beds*, being crowded with a well-preserved mixed molluscous fauna among which Gasteropods predominate; but Brachiopods, Lamellibranchs, and Ammonites are well represented.

The zonal fossil of the St Cassian Beds is *Trachyoceras aon*. It is notable that, although the St Cassian fauna is so prolific and varied, the forms are mostly stunted and small.

The *Great Dolomite* or *Lower Dachstein Limestone* which closes the Trias proper in Southern Europe, consists of several thousand feet of thin-bedded, platy, and unbedded limestone, and is distinguished by the zonal fossils *Avicula exilis* and *Turbo solitarius*.

The **Rhætic Series** consists principally of dolomitic limestones, marls, and sandstones. It forms a thin but continuous sheet, which is present in Germany and England as well as in the Alpine region, thereby proving that the partial separation of the Germanic Basin and the seas of Southern Europe ceased at this stage of the Trias.

The Trias in Other Countries.

India.—The Continental and Marine facies of the Trias are well represented in Northern India, and, as in Europe, they occur in separate geographical provinces.

The Triassic division of the Permo-Jurassic Gondwana System contains a scanty flora which includes several species of *Glossopteris*, and the beautiful fern *Danacopteris Hughesi*, found also in Tonkin and China. Besides these it contains the remains of amphibians; and among the fish remains there is a form related to the *Ceratodus* of the Trias of Europe.

The Trias of the Gondwana System is obviously of continental origin, and corresponds to the German facies of Central Europe. The Indian Gondwana, as previously described, includes three main divisions, the Lower, Middle, and Upper, which correspond with the Permian, Trias, and Jurassic. The main divisions are as follow:—

Gondwana System	Jubbulpore Series Rajmahal Series	. . .	Jurassic.
	Mahadeva Series	Maleri Stage Kamthi Stage Panchet Stage	Triassic.
	Damuda Series Talchir Series	. . .	Permian.

The Gondwana System contains the most important coal-bearing formations in India. Valuable coal-seams occur in both the Jurassic and Permian divisions, but at the present time the domestic supplies of India are mostly drawn from the Damuda Series.

The Marine or Alpine Trias of India is splendidly developed in the Salt Range of the Punjab, in Baluchistan, and Tibetan Plateaux in Western Tibet. The rocks are mainly limestones interbedded with marly and shaly rocks. Fossils are exceedingly abundant and generally well preserved. Among the fossils recognised in these beds are the European species *Ammonites floridus*, *A. diffusus*, *Halobia Lommeli*, *Monotis salinaria* (Plate XXXVIIIB. fig. 1), and *Megalodon scutatus*.

To face page 380.] [PLATE XXXVIIIB.

FIG. 1.

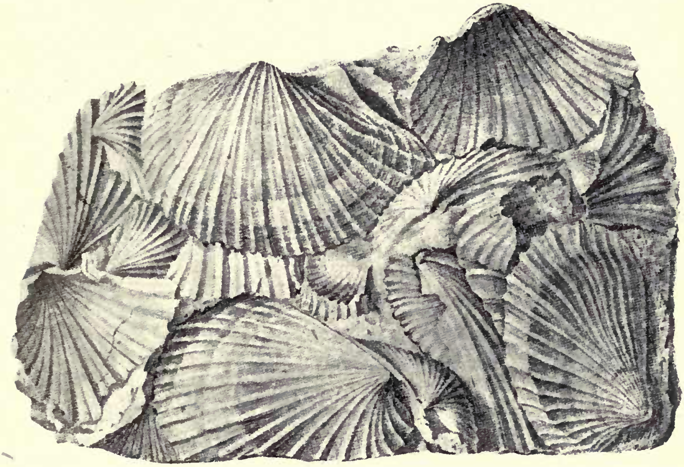

FIG. 2.

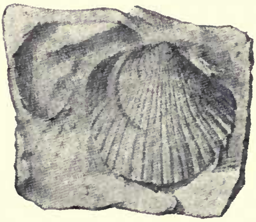

FIG. 3.

TYPICAL TRIASSIC FOSSILS OF ALPINE FACIES.

FIG. 1. *Monotis salinaria* var. *Richmondiana* (Zittel).
FIGS. 2 and 3. *Halobia Lommeli* (Wissm.).

Australasia.—Triassic rocks are well developed in Queensland, New South Wales, and New Zealand.

The Trias of New South Wales consists of three distinct groups :—

3. The Wianamatta Shales.
2. The Hawkesbury Sandstone.
1. Narrabeen Shales.

These rocks are of continental origin and hence belong to the German facies of the Trias. They contain thin seams of coal and numerous plant remains, among which are found the characteristic genera *Tænopteris*, *Thinnfeldia*, and *Sphenopteris*. Fish remains are not uncommon.

In New Zealand the Trias forms the middle division of the Hokonui System. It consists of a vast pile of sandstones, shales, and conglomerates of estuarine and fluviatile origin intercalated with marine beds which contain many of the characteristic species of the Alpine Trias of Southern Europe and India, notably *Halobia Lommeli* and *Monotis salinaria*. The limestones which dominate the marine Trias of the Northern Hemisphere are entirely unknown, and calcareous rocks of all kinds are conspicuously absent.

Among the fossils present in the marine beds are the Brachiopods *Athyris, Spiriferina, Terebratula, Rhynchonella*; the Lamellibranchs *Trigonia, Megalodon, Ostrea*, and *Mytilus*; and the Gasteropods *Murchisonia* and *Pleurotomaria*. Cephalopods are represented by a large *Nautilus* and a few species of Ammonites, but they are scarce and badly preserved. There are no corals and bryozoans.

The beds of conglomerate contain pebbles of granites and other igneous rocks that are unknown in the present land surface of New Zealand.

The New Zealand area in the Triassic period appears to have formed the southern coasts of a continental region that lay to the north-west in the present Tasman Sea, and was drained by large rivers that discharged their load of sand and mud in shallow deltaic seas. The prevalence of muddy sediments was probably responsible for the absence of coral-building polyps and the scarcity of Ammonites and deep-water Cephalopods.

Some of the clayey and sandy beds are crowded with broken plant remains; and in the shallow-water marine beds there are sometimes found saurian remains, among which the genus *Ichthyosaurus* has been doubtfully identified.

Among the plants recognised by Dr Arber from the late Trias (Rhætic) or very early Jurassic rocks of New Zealand, are the genera *Thinnfeldia, Cladophlebis, Tæniopteris, Sphenopteris, Pterophyllum*, and *Palissya*.

Antarctic Continent.—Sandstones and shales of Trias-Jura age occur in the north-east end of Graham's Land, in the Antarctic region. They contain a rich and varied flora embracing ferns, cycads, and conifers. Among the plants are the genera *Sagenopteris*, *Thinnfeldia*, *Cladophlebis*, *Pterophyllum*, and *Otozamites*, all of which are found in the older Mesozoic rocks of Northern India and Eastern Australia, and some are found in the Argentine.

The presence of these plants would indicate a mild and moist climate during the Jurassic period, where now the land is covered with permanent ice and snow.

In Victoria Land the *Beacon Sandstone Series* covers a large tract of country. The sandstones are horizontal and intercalated with shales and seven coal-seams capped with a thick flow of dolerite, and intruded by sills of the same rock. The plant remains found in the sandstones are too fragmentary for critical determination. Hence the age of this formation may be older or younger than Trias.

South Africa.—The Karoo System of South Africa appears to be approximately the equivalent of the Gondwana System of India. It consists of a great succession of sandstones, shales, and conglomerates, with coal-seams and plant beds. All the known fossils are land or freshwater forms, and nowhere do the rocks contain evidence of marine conditions of deposition.

The lower divisions contain a *Glossopteris* flora, and the middle a flora related to that of the Middle Gondwana, as well as a remarkable assemblage of reptiles and lizards. The rock-salt and gypsum beds which characterise the continental conditions of deposition in the Northern Hemisphere are entirely absent. It would therefore appear that the Karoo deposits were laid down in great inland freshwater basins fringed with mud-flats that swarmed at certain stages with reptiles and amphibians. The climate was probably tropical or semi-tropical, but the numerous reptilians and coal-seams would seem to indicate the absence of arid desert conditions.

The Karoo System comprises four main divisions, namely :—

4. Stormberg Series.
3. Beaufort ,,
2. Ecca ,,
1. Dwyka ,,

The *Dwyka Series*, as already described, is dominated by glacial conglomerates. The *Ecca Series* contains a *Glossopteris* flora related to the Permian facies of the Lower Gondwana. Among the genera of land plants common to the two systems are *Glossopteris*, *Gangamopteris*, *Nœggerathiopsis*, *Schizoneura*, *Phyllotheca*, and *Sphenopteris*, many of which are also found in the Lower and

Upper Coal-Measures of New South Wales, the Bowen River Series of Queensland, the Lower Coal-Measures of Tasmania, and also in the Trias of Brazil and Argentina.

The *Beaufort Series* is mainly characterised by the occurrence in it of a number of reptilian remains, including representatives of the Anomodontia and Theriodontia, which are almost limited to this series and the Panchet Beds of the Middle Gondwana. Of the Anomodontia there is the peculiar genus *Dicynodon*; and of the Theriodontia, the genera *Placodus* and *Galesaurus*. Among the plants in this series are *Glossopteris* and *Schizoneura*.

The *Stormberg Series* contains fish remains, including those of *Ceratodus* and some Deinosaurs, but is chiefly distinguished by a fairly abundant flora, which includes representatives of *Thinnfeldia*, *Tæniopteris*, and *Sphenopteris*, which are also found in the Upper Gondwana of India, the Triassic Hawkesbury Sandstone of New South Wales, and the Upper Coal Series of Tasmania. But correlations based on the fragmentary remains of a scanty land flora, indicating a continuance of the same physical conditions and showing little progressive development through a long period of time, are never trustworthy or satisfactory.

North America.—The Continental and Marine facies of the Trias are typically developed in North America, the former in the Eastern States and Central Basin, and the Marine in the Pacific States.

Continental Facies.—In the Eastern States a chain of disconnected patches of the Trias extend from Nova Scotia to South Carolina, running parallel with the present coast-line and the Appalachian Chain. The largest developments are found about the Bay of Fundy, in Connecticut River Valley, and in a belt extending southward from South New York to New Jersey, Pennsylvania, Maryland, and Virginia.

Everywhere the Trias lies unconformably on the underlying formations. The rocks are mainly sandstones and shales, with which are interbedded massive bands of conglomerate and breccia.

In New Jersey, where the continental Trias is well developed, the system has been divided into three distinct groups:—

$$\text{Newark System}\left\{\begin{array}{l}\text{3. Brunswick}\\ \text{2. Lockatong}\\ \text{1. Stockton}\end{array}\right\}\text{Triassic.}$$

The rocks of the Newark System are poor in fossils, which comprise land plants, fresh- and brackish-water fishes, and the teeth of reptiles. The prevailing colour of the sandstones and shales is red. The character of the sediments and their fossils clearly show that deposition took place in large inland basins.

Triassic rocks of a similar character, but containing beds of rock-salt and gypsum, occupy large tracts in Texas, South Dakota, and Wyoming; and a belt of the same rocks extends along the eastern base of the Rocky Mountains from Western Canada to New Mexico.

The plant life of this period contained numerous cycads, ferns, and conifers, the latter including the genera *Palissya*, *Albertia*, and *Ullmania*. The ginkgos were represented by *Baiera*, which also occurs in the Upper Karoo, and first appeared in the Permian of Central Germany. The Calamites are replaced by true horse-tails; but the *Glossopteris* flora, which is so characteristic of this period in India, Australia, and South Africa, is entirely absent, as it also is from Western Asia and Europe.

Land animals were represented by numerous Labyrinthodonts and the curious deinosaurs, a group of reptiles which was at one time believed to possess bird-like affinities. The flying saurian, *Pterosaurus*, appeared for the first time at the close of the period.

Marine Trias.—The greatest development of the North American marine Trias is on the Pacific watershed, in the Sierras, California, West Humboldt Range of Nevada, Oregon, British Columbia, and Alaska. In Nevada the maximum thickness of the system is 17,000 feet, the lower division, known as the *Koipeto Series*, consisting mainly of sandstones and shales, and the upper division, the *Star Series*, of sandstones, quartzites, and limestones. In the West Humboldt Range the rocks of the Star Series are sharply folded and highly metamorphosed.

The marine fauna of this system includes many European genera, among which we have the Cephalopods *Trachyoceras*, *Ceratites nodosus*, and *Orthoceras*; the Lamellibranchs *Corbula*, *Myophoria*, and *Pecten*; and the Brachiopods *Terebratula*, *Rhynchonella*, and *Spiriferina*.

Surface Features.—In England, where the Triassic rocks are mostly sandstones and shales, the Triassic areas usually exhibit gentle undulating contours. In Germany the argillaceous Keuper also forms outlines of low relief; but in the South Tyrol, where the Muschelkalk is strongly developed, the softer marls have been worn away, and the limestone bands stand up as high, tent-shaped, craggy ridges and bold escarpments that combine to form the picturesque beauty for which the mountains of that region are famous.

Economic Products.—In England the Triassic rocks contain valuable beds of rock-salt, which are important as a source of the British salt supplies. The principal salt-producing areas are situated in Cheshire, Worcestershire, and North Yorkshire.

The rock-salt and gypsum beds in Texas and South Dakota are extensively worked and of considerable value.

The red sandstone and massive dolomitic limestones of the

Triassic System are used for building purposes in many parts of Europe, America, and Australia.

Triassic rocks do not contain metalliferous deposits of any moment. Coals of Devonian, Carboniferous, and Triassic age occur in Turkestan, but so far only the Triassic coals have been worked on a commercial scale.

CHAPTER XXIX.

JURASSIC SYSTEM.

THE Jurassic is the upper division of the great succession of conformable strata of which the Triassic forms the middle division and the Permian the lower. It represents the continuation of the marine conditions of deposition ushered in by the Rhætic as the result of the subsidence which set in towards the close of the Triassic period. The Rhætic acts the part of *passage* or *transition beds* connecting the two systems, and is sometimes placed at the close of the Triassic and sometimes at the base of the Jurassic.

The name Jurassic was derived from the Jura Mountains in West Switzerland, where rocks of this age are typically developed.

Rocks.—The rocks comprising the Jurassic System in the Northern Hemisphere are mainly marine marls and limestones, with subordinate beds of sandstones and shales, with which seams of coal are sometimes associated. The conditions of deposition were mainly marine, but estuarine and terrestrial conditions were introduced in some regions through slight oscillations of the land.

In the Southern Hemisphere the rocks are mainly sandstones and shales of the continental facies; and limestones are conspicuously absent, except perhaps in some parts of South America.

Different Facies of Deposits.—It should always be remembered that the lithological character of the rocks comprising a formation bears no relation whatever to the age of the formation, but is merely an expression and record of the physical geography of the region in which the deposition of the sediments took place.

Let us once more briefly summarise the physical conditions in which clastic rocks are formed.

In past geological ages, as now, there always existed deep seas fringed with shallow estuaries and deltas, open bays and land-locked harbours, seas bounded by high, rugged coasts and by wide maritime plains, Mediterranean seas and inland salt-water seas of the Dead Sea type, and great inland freshwater lakes, some situated in humid, others in arid deserts. In all the seas, estuaries, and inland lakes existing at the same time, sediments were laid down contemporaneously, the various deposits enclosing representatives of the faunas and floras that peopled the waters and clothed the neighbouring lands.

We have already seen that in the Devonian, Carboniferous, Permian, and Triassic periods there were laid down two facies of deposits—the marine and continental—each characterised by the sediments and life peculiar to the conditions of deposition. These two facies are also found in the Jurassic, and they have doubtless been formed throughout all geological time, or ever since the great continents came into existence, just as they are forming at the present time.

Coral reefs, coralline sands, and muds are now forming on the north-east coast of Australia, and vast sheets of estuarine sands and muds are accumulating in the shallow seas fringing the northern coasts; while in the centre of that ancient and worn-down continent we find great lake-basins which are now completely filled with brick-red, wind-borne sands and desert soils, or the remains of basins now marked by chains of brackish-water lagoons and swamps, frequently encrusted with layers of rock-salt.

The coral reefs, coralline sands, and muds represent the marine facies of warm seas; the tidal mud-flats of the north, the estuarine facies; and the red desert sands and clays filling the inland basins, the continental facies of an arid interior.

In later times the marine facies will be represented by massive limestones and marls, with corals, echinoderms, and other distinctive life of clear sea-water; and the continental facies, by red sandstones and shaly clays, current-bedded and sun-cracked, enclosing the remains of the fishes and molluscs that inhabited the lakes, also land plants and the carcases of land animals swept into the basins by the overwhelming inundations that characterise semi-arid regions. In arid regions, where the inland basins were portions of the sea isolated by uplift, the sandstones and shales may be intercalated with lenticular beds of rock-salt and gypsum, but in humid regions favourable for the growth of a rank vegetation and the accumulation of peaty deposits, the continental beds may be associated with seams of coal.

The estuarine and deltaic sediments are mainly fluvio-marine. On the seaward side they pass into marine deposits, and on the landward into terrestrial. They will contain the remains of the crustaceans and molluscs that find a congenial habitat on tidal mud-flats and sandy shell-banks, mingled with the leaves, twigs, and trunks of land plants, the carcases of land animals carried down by rivers, and the shells of marine molluscs cast up by high tides and storms. On the wide mud-flats lying above the influence of the tides, the accumulation of peaty matter may form the material for extensive seams of coal. If the land subsides, the sea will encroach on the swampy lands, whereby the peats may become covered with a protecting sheet of sands and muds, and thereby be preserved from destruction. If further subsidence takes place, the estuarine sands may become covered with marine deposits. If an uplift now takes place, the sea will once more retreat, and we may get a repetition of the first conditions, with a new growth of vegetation on the former site, but on a new soil separated from the old by the layers of sand and mud previously laid down.

Hence, when we take a general view of a world-wide formation, such as the Jurassic, we must expect to find considerable diversity in the character of the rocks and fossil remains, notwithstanding that they may be contemporaneous; and since the estuarine is merely a pathological phase of the marine, the two distinctive genetic types of deposits must always be the *marine* and *continental*.

Distribution.—The Jurassic System is extensively developed in England, France, Germany, European and Asiatic Russia, Asia Minor, India, Japan, Borneo, New Guinea, Australia, New Zealand, South Africa, Chile, Peru, Bolivia, Western States of America, and Alaska.

Although the Jurassic was not a period of mountain-building, we know that widespread land movements took place in the eastern side of the North American continent, in European and Asiatic Russia, and India.

The entire absence of Jurassic rocks in the Eastern States of North America shows that the uplift of that region lasted throughout the whole of this period, but such uplift did not affect the western portion of the continent, where sediments continued to be laid down in the Triassic areas up to the close of the Jurassic, which means that the uplift of the rocks and retreat of the sea on the east coast was balanced by subsidence of the rocks and advance of the sea on the west coast. Here the axis of the tilting movement followed a north and south direction, and passed through the great Western Interior Basin, bounded on the east by the Rocky Mountains.

In England, France, Germany, and Southern Europe, the whole of the Jurassic is present, but in the Baltic area and European Russia the lower half of the system is absent, thereby proving that the continuous subsidence in Southern Europe was compensated in the northern region by uplift during the lower half of the period, and by subsidence during the upper half. Here the axis of the tilting movement followed an approximately north-west and south-east direction.

In India, where the marine Jurassic rocks are distributed in two distinct geographical areas, each characterised by a peculiar facies, the one in the Inner Himalayas and Tibetan region, the other in the coastal region, the canting movement was the converse of that in Europe and Western Asia.

In the coastal or southern area the lower half of the system is absent, while in the Himalayan area the lower is present and the upper absent or greatly interrupted. Here we have evidence that the uplift in the south during the lower half of the Jurassic was balanced by subsidence in the north, and that the uplift in the north during the upper half of the period was balanced by subsidence in the south. The axis of this rhythmical see-saw movement was about north-west and south-east, or parallel with the tilt-axis of Europe.

This singular contrariwise tilting in Europe and India must have caused warping and enormous crustal stress in Western Asia.

Fauna and Flora.—Since the rocks of the Jurassic System, as developed in Europe, Asia Minor, Himalayan region, and Pacific States of North America, are essentially composed of marine sediments, the fossils which they contain for the most part represent the marine life of that period.

Corals are abundant in the limestones, and belong to the aporose and perforate types which have now replaced the rugose and tabulate corals of the Palæozoic era.

Sponges, foraminifera, and radiolarians are plentiful, the former in most cases well preserved.

Crinoids have become scarce, but sea-urchins, which become so prominent in the succeeding Cretaceous period, are represented by *Cidaris*, *Hemicidaris*, *Echinobrissus*, and *Pygaster*, and other echinoids.

The brachiopods are mostly of the Terebratula type, the straight-hinged Spiriferinas being less common than in the Trias.

Of the molluscs, Lamellibranchs, Gasteropods, and Cephalopods are abundant. The Jurassic is specially characterised by the great development of Ammonites, which are so numerous and important that this period has not inappropriately been called *The Age of Ammonites*. Many of the species of Ammonites are world-wide in distribution, and so limited in vertical range that they serve to divide the system into palæontological zones, each distinguished by a characteristic species. The Ammonite zones follow the same order of succession in all parts of the globe.

The Belemnites, a somewhat peculiar type of Cephalopods, make their first appearance in the Jurassic, and attain their maximum development before the close of the period.

Fishes are numerous, and among the genera that appear for the first time are the skates and rays, gar-pikes, sturgeons, and cat-fish. The bony fishes, the Teleosts, which are the dominant existing type, are now represented by several species.

Reptilians which were prominent in the Middle and Upper Trias occur in such extraordinary numbers that the Jurassic is familiarly called *The Age of Reptiles.* The seas, the estuaries and deltas, the dry land and the air, swarmed with reptilians, many of them of huge size and peculiar form.

The marine types are represented by *Ichthyosaurus*[α] and *Plesiosaurus*[β] (Plate XXXIX.. figs. 1 and 2); the land reptiles by the herbivorous deinosaurs,[γ] some of which grew to a length of 80 feet, and a height of over 20 feet; and the flying saurians by *Pterosaurus.*[δ]

The earliest known birds lived in the Jurassic lands. *Archæopteryx,*[ε] found in the lithographic shales of Solenhofen in Bavaria, was provided with true teeth and a pair of feathers on each caudal vertebra.

The Jurassic is further distinguished by the presence of the earliest mammals, the remains of which have been found in England and America. These primitive mammals are believed to belong to the marsupial type, which still survives in the Australian continent.

Plant remains are found in great abundance in the terrestrial and estuarine beds, and tend to show that the Jurassic lands were clothed with a luxuriant vegetation. Cycads attain their maximum development; hence the name *Age of Cycads* sometimes applied to the Jurassic.

Ferns and conifers are also conspicuous, among the latter appearing examples of the ancestral forms of the modern pines, cypresses, and yew.

The remains of insects, including those of beetles, moths, butterflies, and flies, are abundant in the estuarine muds, having doubtless been blown seaward by strong winds. Many of the beetles belong to the tree-boring kinds, which is further evidence of the existence of forest trees on the lands fringing the Jurassic sea coasts.

Subdivisions.—For our first knowledge of the subdivisions of the Jurassic System we are indebted to William Smith, the father of English geology, who in the first decade of the nineteenth century determined the chronological succession of the Middle Mesozoic rocks of England. This work was afterwards supplemented by the investigations of Conybeare, Phillips, and others, and so important a part has the researches of English geologists played in the history of the Jurassic that many of the names used by them have passed

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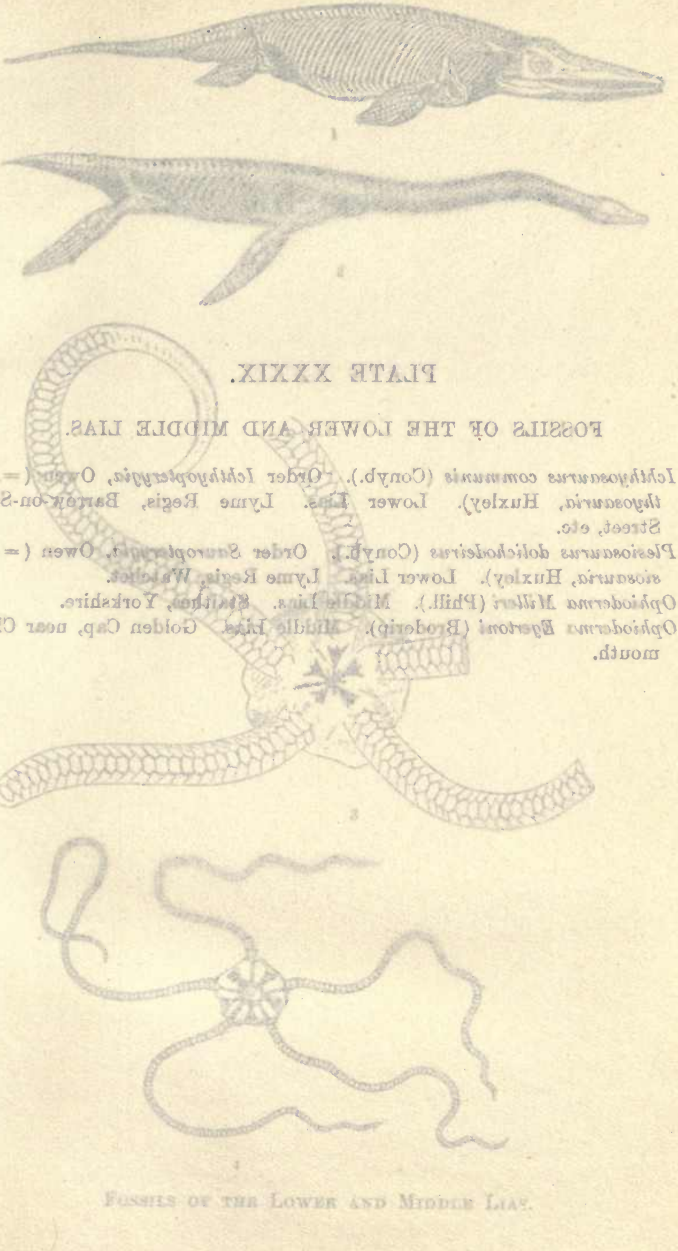
[α] Gr. *ichthys*=a fish, and *sauros*=a reptile.

[β] Gr. *plesios*=near to, and *sauros*=a reptile.

[γ] Gr. *deinos*=terrible, and *sauros*=a reptile.

[δ] Gr. *pteron*=a wing, and *sauros*=a reptile.

[ε] Gr. *arche*=a beginning, and *pteryx*=a wing.

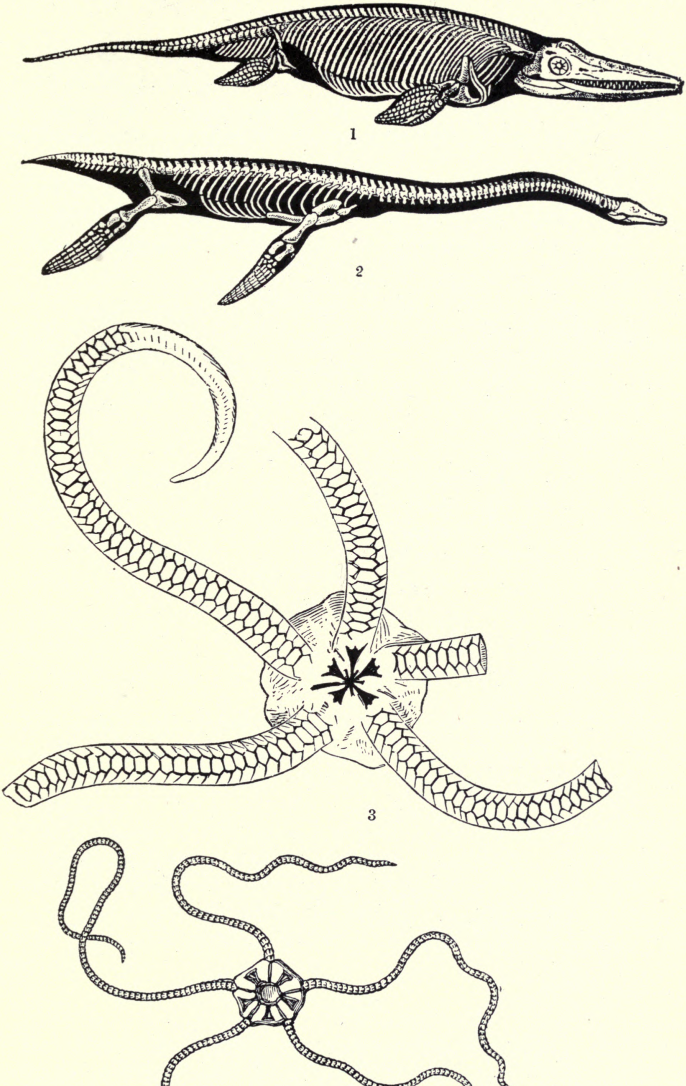


FOSSILS OF THE LOWER AND MIDDLE LIAS.

PLATE XXXIX.

FOSSILS OF THE LOWER AND MIDDLE LIAS.

1. *Ichthyosaurus communis* (Conyb.). Order *Ichthyopterygia*, Owen (=*Ichthyosauria*, Huxley). Lower Lias. Lyme Regis, Barrow-on-Soar, Street, etc.
2. *Plesiosaurus dolichodeirus* (Conyb.). Order *Sauropterygia*, Owen (=*Plesiosauria*, Huxley). Lower Lias. Lyme Regis, Watchet.
3. *Ophioderma Milleri* (Phill.). Middle Lias. Staithes, Yorkshire.
4. *Ophioderma Egertoni* (Broderip). Middle Lias. Golden Cap, near Charmouth.



FOSSILS OF THE LOWER AND MIDDLE LIAS.

into general use throughout the globe. And since the Ammonite zones of England have been found to be almost world-wide in distribution, the subdivisions of the Jurassic, as determined in England, may be described as typical of the system for all other regions.

The Jurassic System is very fully developed in England, France, and Germany. In other countries the succession is incomplete or not sufficiently worked out for comparative purposes.

British Isles.

		England.		Germany.
2. Oolite (Upper Jurassic)	Upper	3. Purbeckian		Upper or White Jura.
		2. Portlandian		
		1. Kimeridgian		
	Middle	2. Corallian		
		1. Oxfordian	Oxford Clay Callovian	
	Lower	2. Bathonian (Great Oolite)		Middle or Brown Jura
		1. Bajocian	Fuller's Earth Inferior Oolite	
1. Lias (Lower Jurassic)	Upper,	. . . . . .		Lower or Black Jura.
	Middle,	. . . . . .		
	Lower	. . . . . .		

The two great divisions of the Jurassic System in England are the *Lias* or Lower Jurassic and the *Oolite* or Upper Jurassic, which correspond to the *Black Jura*, *Brown Jura*, and *White Jura* of Germany.

The Jurassic of England occupies a broad zone extending from the coast of Dorset to the coast of Yorkshire. There are small patches in South Wales, on the border of Cheshire, and further north in Cumberland, Inner Hebrides, and east coast of Sutherland. In Ireland small outcrops occur on the borders of the Antrim plateau.

Lias.

The Lias is essentially an argillaceous formation. In England, and also in France and Germany, it consists mainly of clays and soft shales that vary in colour from grey to black. The clays are sandy in places, and in the lower part of the series in England contains bands of limestone that are sometimes shelly, but most frequently sedimentary, being composed of calcareous muds derived from the denudation of Palæozoic limestones in the neighbourhood.

In the middle or Marlstone division the clays are interbedded with bands of limestone and ironstone, the last a valuable source of iron ore in the Cleveland district of Yorkshire and in the Midland counties.

The shaly clays of the Upper Lias contain a considerable quantity of the marcasite form of pyrite. The decomposition of this ore produces sulphuric acid, which combines with the alumina of the clay and forms alum, which appears as an efflorescence on the surface of the rock.

The remains of insects are plentiful in the clays and shales. The muddy, shallow seas in which the Lias was deposited did not favour the growth of corals and bryozoans or the existence of echinoderms, all of which are rare.

The characteristic brachiopods are *Spiriferina Walcottii* (Plate XLI., fig. 4), and *Rhynchonella tetrahedra.*

Among the abundant Lamellibranchs are *Gryphæa arcuata* (Plate XL., fig. 3), *Lima gigantea* (Plate XL., fig. 2), and *Hippopodium ponderosum* (Plate XLI., fig. 2).

Fishes are well represented, but the most important vertebrates are the reptilians, which included the marine saurians, *Ichthyosaurus* and *Plesiosaurus*, as well as flying Pterodactyls.

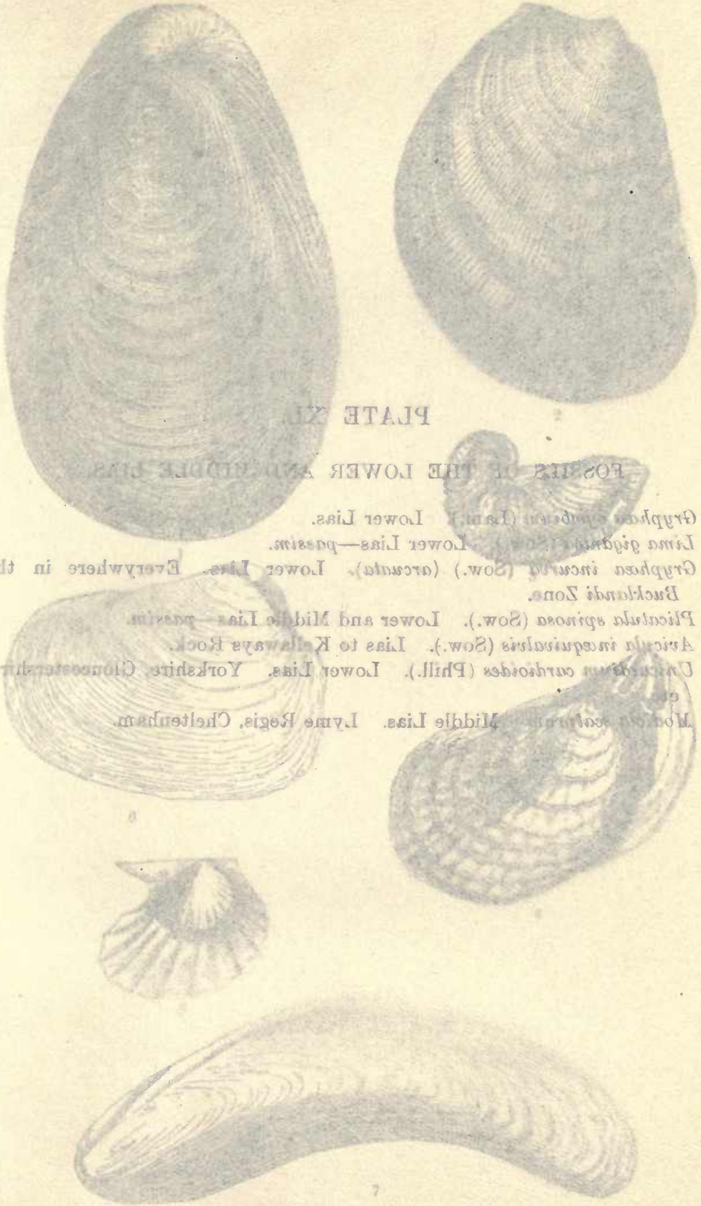
Ammonites are numerous and have been used to divide the layers into zones, each characterised by a particular species, as shown below :—

Upper Lias	Zone of	*Ammonites*	*jurensis.*
	,,	,,	*communis.*
	,,	,,	*serpentinus.*
Middle Lias	,,	,,	*spinatus.*
	,,	,,	*margaritatus.*
Lower Lias	,,	,,	*capricornus.*
	,,	,,	*jamesoni.*
	,,	,,	*oxynotus.*
	,,	,,	*bucklandi.*
	,,	,,	*planorbis.*

Lower Oolite.

The various divisions of the Lower Oolite are local in distribution and variable in thickness. Most of them are well developed in Dorset and South-West District, but they thin out rapidly going toward the north-east, and many of them disappear entirely before the borders of Oxfordshire are reached. Only one bed, the *Cornbrash*, the closing member of the Lower Oolite, is persistent from the south-west coast to the coast of Yorkshire.

The name *Oolite* applied to the limestones of the Upper Jurassic

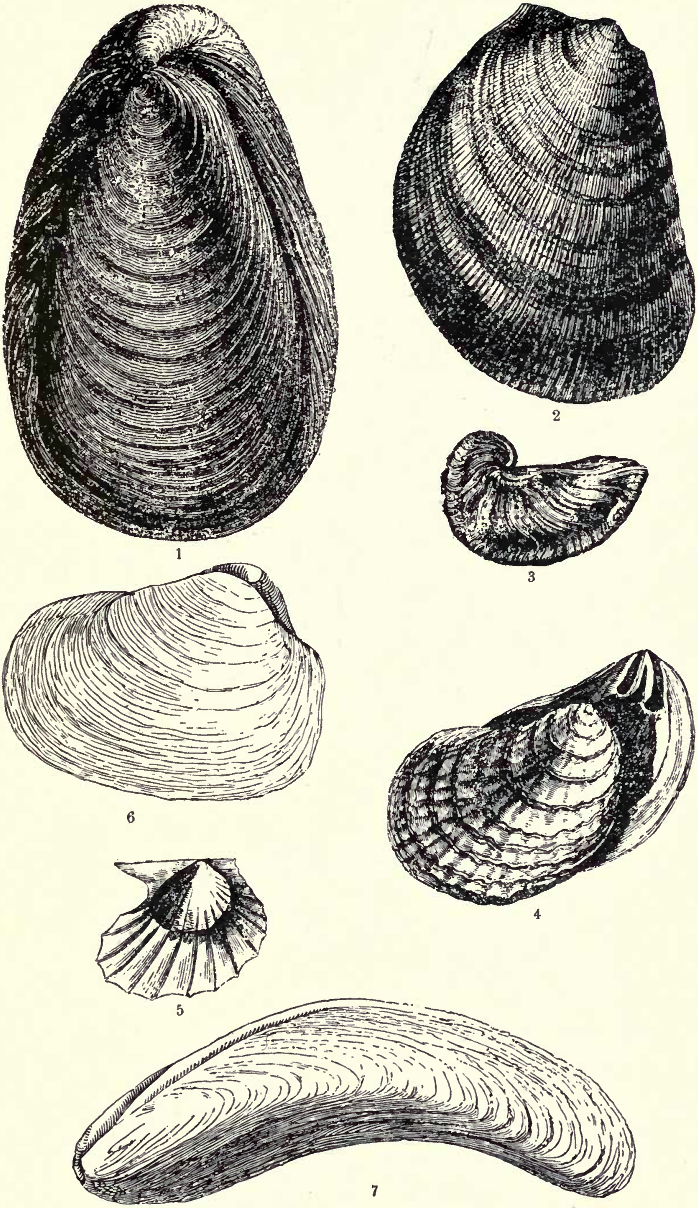


FOSSILS OF THE LOWER AND MIDDLE LIAS.

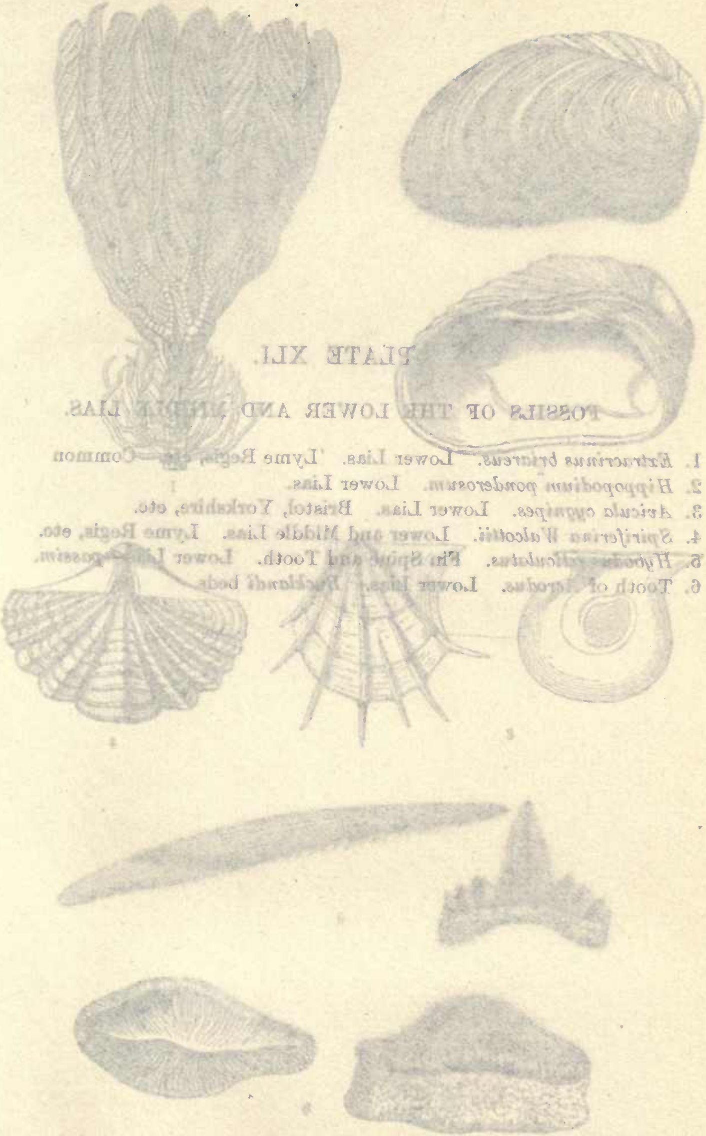
PLATE XL.

FOSSILS OF THE LOWER AND MIDDLE LIAS.

1. *Gryphæa cymbium* (Lam.). Lower Lias.
2. *Lima gigantea* (Sow.). Lower Lias—*passim.*
3. *Gryphæa incurva* (Sow.) (*arcuata*). Lower Lias. Everywhere in the *Bucklandi* Zone.
4. *Plicatula spinosa* (Sow.). Lower and Middle Lias—*passim.*
5. *Avicula inæquivalvis* (Sow.). Lias to Kellaways Rock.
6. *Unicardium cardioides* (Phill.). Lower Lias. Yorkshire, Gloucestershire, etc.
7. *Modiola scalprum.* Middle Lias. Lyme Regis, Cheltenham.



Fossils of the Lower and Middle Lias.



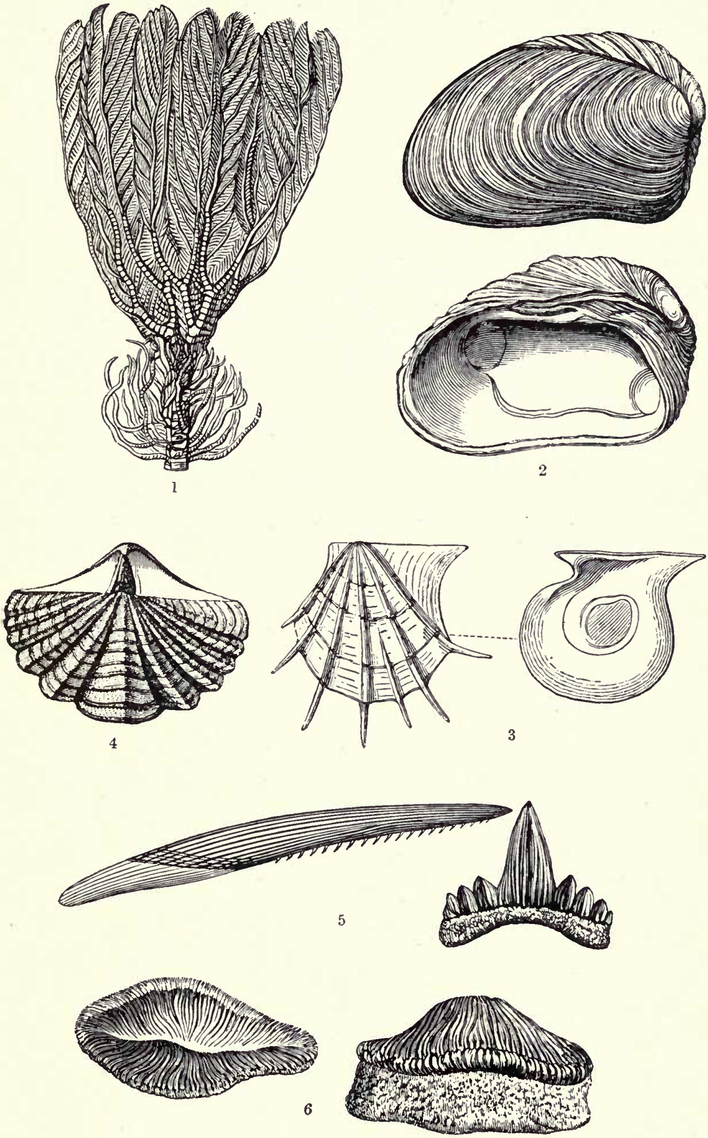
FOSSILS OF THE LOWER AND MIDDLE LIAS.

PLATE XLI.

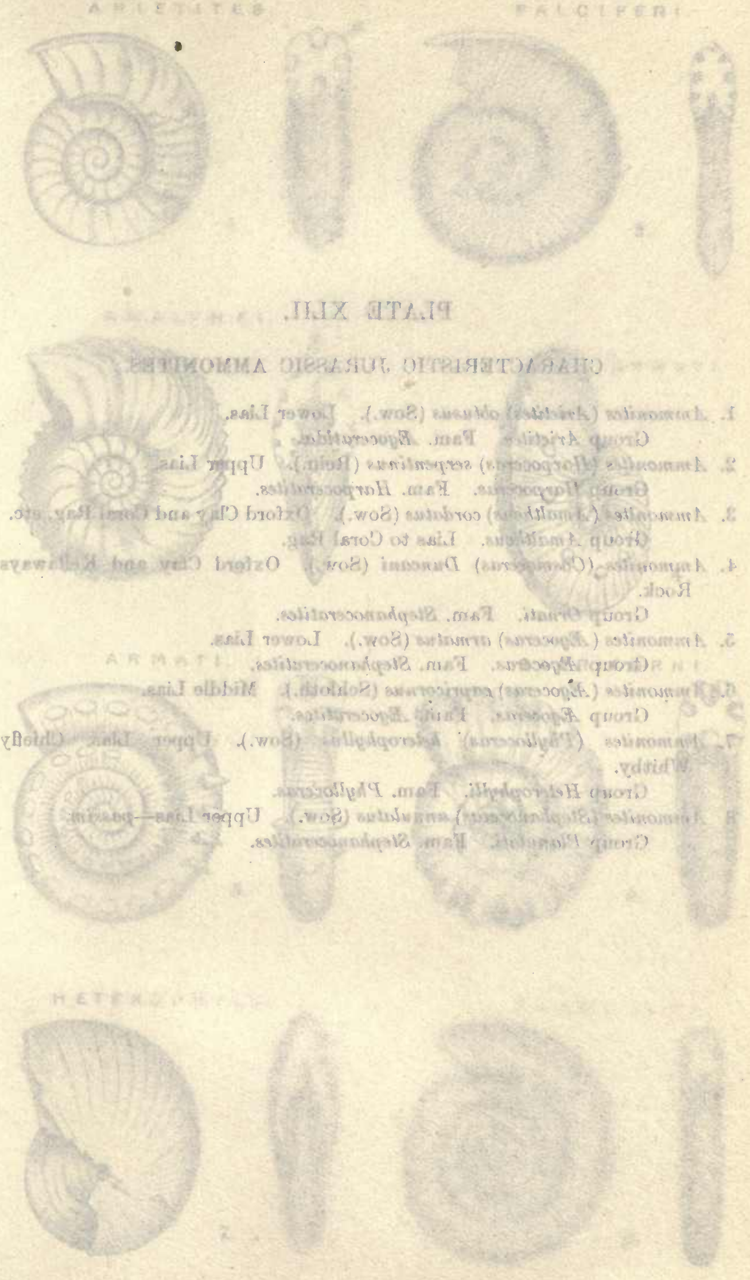
FOSSILS OF THE LOWER AND MIDDLE LIAS.

1. *Extracrinus briareus.* Lower Lias. Lyme Regis, etc. Common
2. *Hippopodium ponderosum.* Lower Lias.
3. *Avicula cygnipes.* Lower Lias. Bristol, Yorkshire, etc.
4. *Spiriferina Walcottii.* Lower and Middle Lias. Lyme Regis, etc.
5. *Hybodus reticulatus.* Fin Spine and Tooth. Lower Lias—*passim.*
6. Tooth of *Acrodus.* Lower Lias. *Bucklandi* beds.

[PLATE XLI.



FOSSILS OF THE LOWER AND MIDDLE LIAS.



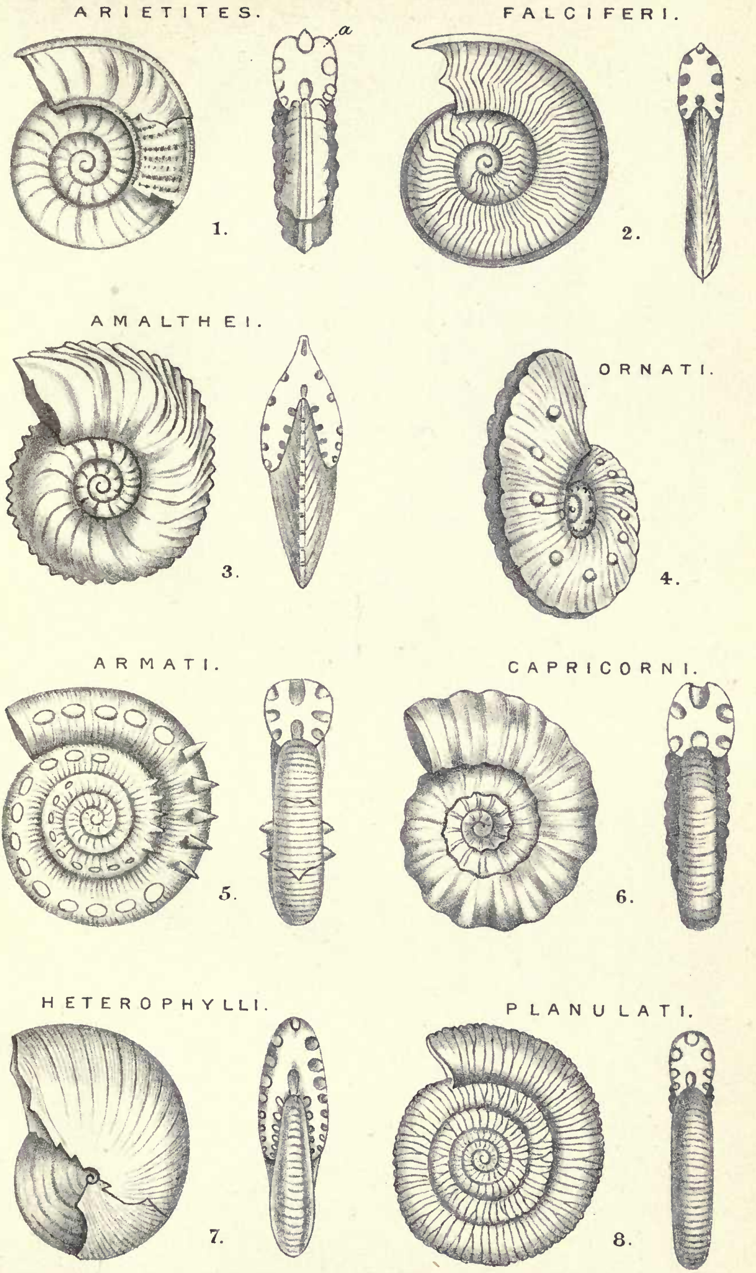
CHARACTERISTIC JURASSIC AMMONITES.

PLATE XLII.

CHARACTERISTIC JURASSIC AMMONITES.

1. *Ammonites* (*Arietites*) *obtusus* (Sow.). Lower Lias.
   Group *Arietites*. Fam. *Ægoceratidæ*.
2. *Ammonites* (*Harpoceras*) *serpentinus* (Rein.). Upper Lias.
   Group *Harpoceras*. Fam. *Harpoceratites*.
3. *Ammonites* (*Amaltheus*) *cordatus* (Sow.). Oxford Clay and Coral Rag, etc.
   Group *Amaltheus*. Lias to Coral Rag.
4. *Ammonites* (*Cosmoceras*) *Duncani* (Sow.). Oxford Clay and Kellaways Rock.
   Group *Ornati*. Fam. *Stephanoceratites*.
5. *Ammonites* (*Ægoceras*) *armatus* (Sow.). Lower Lias.
   Group *Ægoceras*. Fam. *Stephanoceratites*.
6. *Ammonites* (*Ægoceras*) *capricornus* (Schloth.). Middle Lias.
   Group *Ægoceras*. Fam. *Ægoceratites*.
7. *Ammonites* (*Phylloceras*) *heterophyllus* (Sow.). Upper Lias. Chiefly Whitby.
   Group *Heterophylli*. Fam. *Phylloceras*.
8. *Ammonites* (*Stephanoceras*) *annulatus* (Sow.). Upper Lias—*passim*.
   Group *Planulati*. Fam. *Stephanoceratites*.

PLATE XLII.



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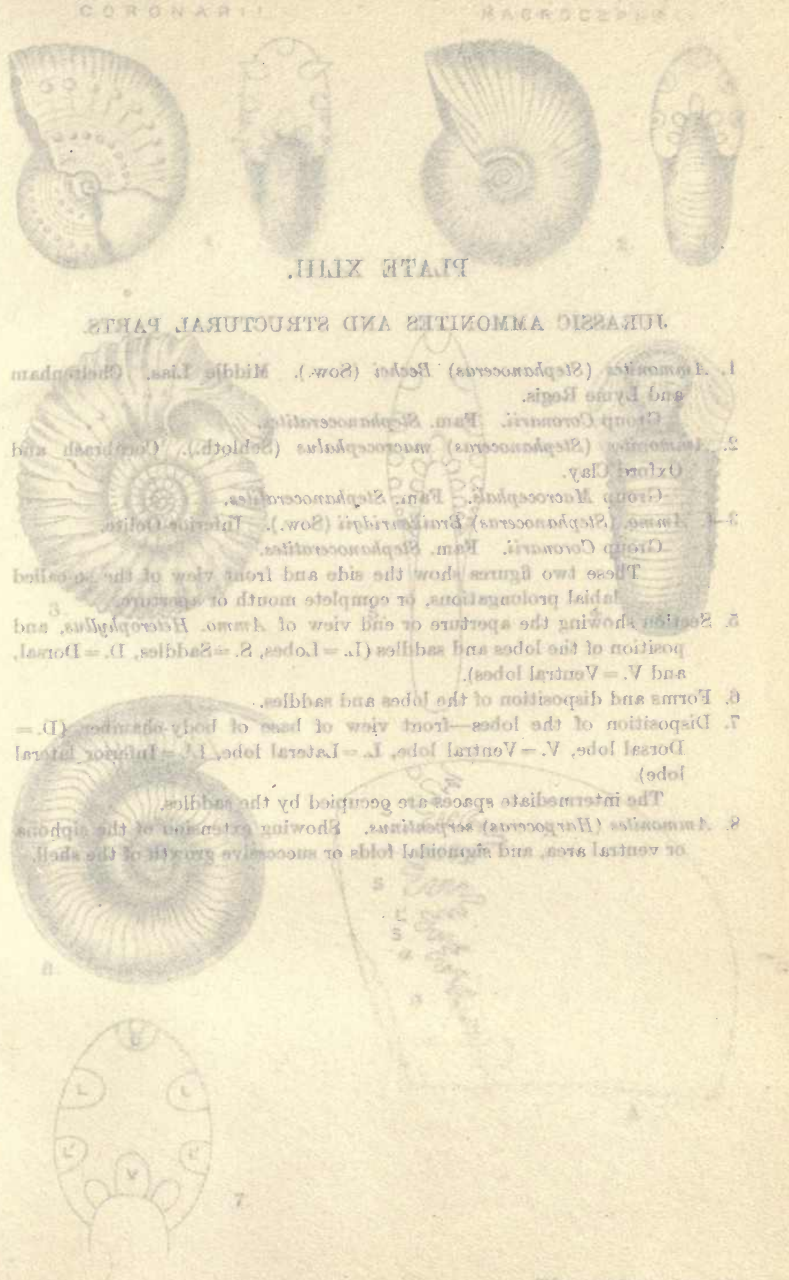
CHARACTERISTIC JURASSIC AMMONITES.



JURASSIC AMMONITES AND STRUCTURAL PARTS.

PLATE XLIII.

JURASSIC AMMONITES AND STRUCTURAL PARTS.

1. *Ammonites* (*Stephanoceras*) *Bechei* (Sow.). Middle Lias. Cheltenham and Lyme Regis.
   Group *Coronarii*. Fam. *Stephanoceratites*.
2. *Ammonites* (*Stephanoceras*) *macrocephalus* (Schloth.). Cornbrash and Oxford Clay.
   Group *Macrocephali*. Fam. *Stephanoceratites*.

3–4. *Ammo.* (*Stephanoceras*) *Braikenridgii* (Sow.). Inferior Oolite.
   Group *Coronarii*. Fam. *Stephanoceratites*.
   These two figures show the side and front view of the so-called labial prolongations, or complete mouth or aperture.

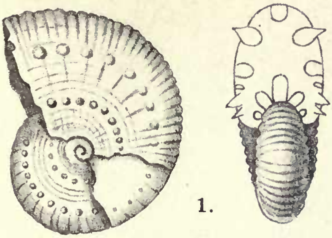
5. Section showing the aperture or end view of *Ammo. Heterophyllus*, and position of the lobes and saddles (L. = Lobes, S. = Saddles, D. = Dorsal, and V. = Ventral lobes).
6. Forms and disposition of the lobes and saddles.
7. Disposition of the lobes—front view of base of body-chamber (D. = Dorsal lobe, V. = Ventral lobe, L. = Lateral lobe, L^1. = Inferior lateral lobe).
   The intermediate spaces are occupied by the saddles.
8. *Ammonites* (*Harpoceras*) *serpentinus*. Showing extension of the siphona or ventral area, and sigmoidal folds or successive growth of the shell.

PLATE XLIII.

To face page 392.

CORONARII.

MACROCEPHALI.



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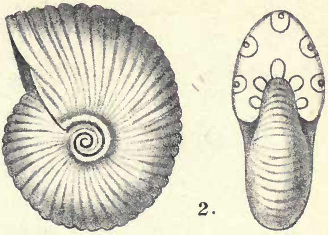

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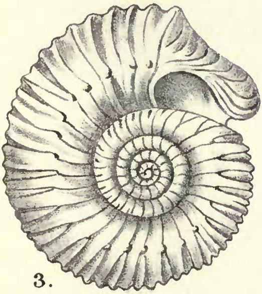

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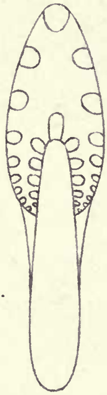

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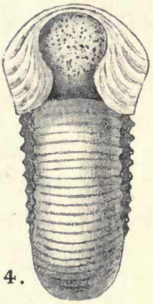

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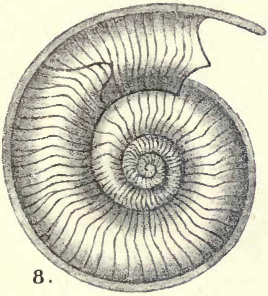

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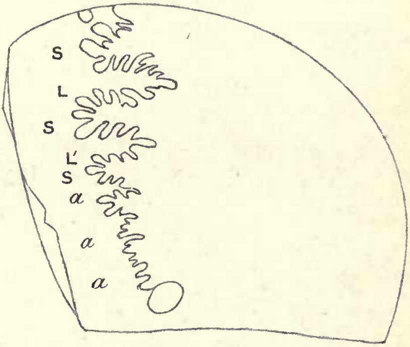

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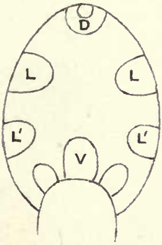

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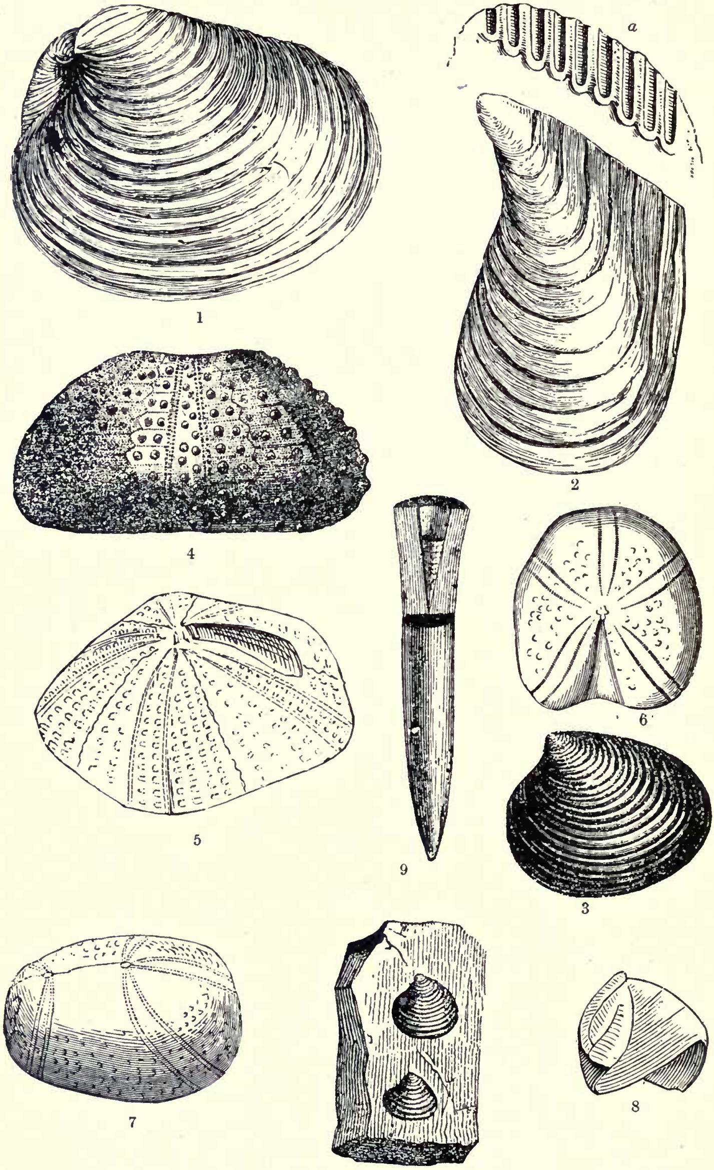
JURASSIC AMMONITES AND STRUCTURAL PARTS.

[PLATE XLIV.



LOWER JURASSIC FOSSILS.

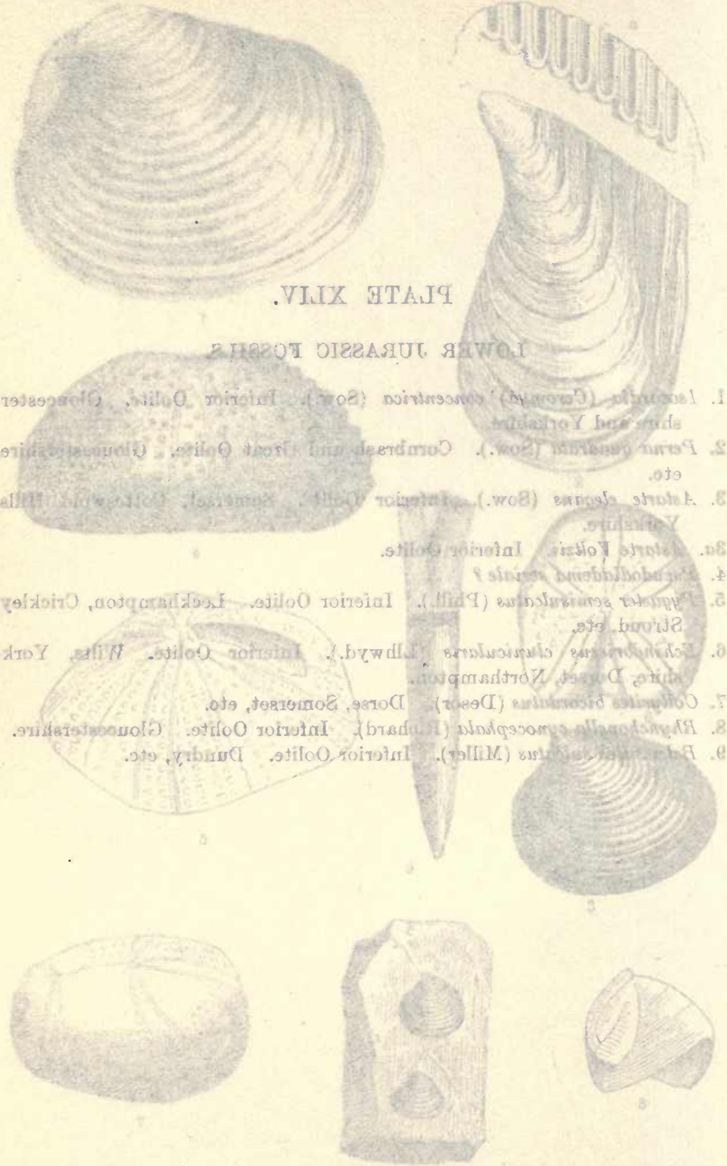
PLATE XLIV.

LOWER JURASSIC FOSSILS.

1. *Isocardia* (*Ceromya*) *concentrica* (Sow.). Inferior Oolite. Gloucestershire and Yorkshire.
2. *Perna quadrata* (Sow.). Cornbrash and Great Oolite. Gloucestershire, etc.
3. *Astarte elegans* (Sow.). Inferior Oolite. Somerset, Cotteswold Hills, Yorkshire.

3*a*. *Astarte Voltzii*. Inferior Oolite.

4. *Pseudodiadema seriale ?*
5. *Pygaster semisulcatus* (Phill.). Inferior Oolite. Leckhampton, Crickley, Stroud, etc.
6. *Echinobrissus clunicularis* (Llhwyd.). Inferior Oolite. Wilts, Yorkshire, Dorset, Northampton.
7. *Collyrites bicordatus* (Desor). Dorse, Somerset, etc.
8. *Rhynchonella cynocephala* (Richard). Inferior Oolite. Gloucestershire.
9. *Belemnites sulcatus* (Miller). Inferior Oolite. Dundry, etc.



LOWER JURASSIC FOSSILS.

in England is derived from the peculiar roe-like grains of calcite of which the limestones are composed.

The characteristic limestone bands of the south are replaced, going northward, by marine sandy beds, which in Yorkshire become typically estuarine, and are locally called the *Estuarine Series*, which is the equivalent of the Inferior Oolite.

On account of the change in the character of the sediments and fossils, the Ammonite zones of the south cannot be traced into the north.

Bajocian.—This stage name is derived from Bayeux, in the Norman Department of Calvados in France, where the Lower Oolite is well developed. In England it is divided into two sub-stages :—

2. Fuller's Earth.
1. Inferior Oolite.

Inferior Oolite.—This follows the Lias conformably, and extends from Dorset north-east to Yorkshire. In the South-West District it consists mainly of shelly marine limestones interbedded with clays and sandstones, but going northward the deposits in Lincolnshire contain an estuarine facies in which freshwater genera, such as *Unio* and *Cyrena*, replace the Ammonites so common in the south. Still further north, in Yorkshire, the strata consists mainly of estuarine sandstones and shales, with bands of ironstone and coal together with several calcareous beds of marine origin. These estuarine beds comprise the well-known *Estuarine Series* of Yorkshire.

The marine beds of the south-west district, which attain a thickness of 264 feet at Cheltenham, contain an abundant fauna, which includes several genera of corals, the crinoid *Pentacrinus*, and a few starfish, including *Goniaster* and *Stellaster*, as well as the sea-urchin *Cidaris*, distinguished by its club-like spines.

Of Brachiopods, *Terebratula* and *Rhynchonella* (Plate XLIV.) are fairly abundant; and among the Lamellibranchs, *Lima*, *Ostrea*, *Pecten*, *Pinna*, *Astarte* (Plates XLIV. and XLVII.), *Cucullæa*, *Mytilus*, *Pholadomya*, and *Trigonia* are common. Gasteropods are numerous, especially the genera *Cerithium*, *Pleurotoma*, and *Turbo*. The Cephalopods include many genera of Ammonites, Nautili, and the peculiar dart-shaped Belemnites.[1]

The palæontological zones of the marine facies of the Inferior Oolite are in descending order :—

4. Zone of *Ammonites Parkinsoni*.
3. ,, ,, *Humphriesianus*.
2. ,, ,, *Murchisonæ*.
1. ,, ,, *opalinus*.

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[1] Gr. *belemnon* = a dart.

The estuarine facies of the Inferior Oolite in Yorkshire contains an abundant fossil flora which comprises many ferns, cycads, and conifers.

The ferns include *Pecopteris*, *Sphenopteris*, and *Tæniopteris*, (Plate XLV.).

The cycads include *Zamites*, *Otozamites*, and *Cycadites*.

The conifers include *Walchia*, *Araucarites*, and *Taxites*.

The three calcareous beds intercalated in the estuarine series are the *Dogger* at the base, with valuable bands of concretionary iron-stone; the so-called *Millepore Limestone*, so named from the abundance of *Millepora straminea*; and the *Scarborough Limestone*.

Fuller's Earth.—This bed extends from Dorset to Bath and Cheltenham, but it is absent in the north-east countries. Its thickness nowhere exceeds 150 feet. It contains numerous fossils, which include many examples of *Ostrea*, *Rhynchonella*, *Magellania*, and *Ammonites*. The clays of this sub-stage are commercially useful for the fulling of cloth; hence the origin of the name.

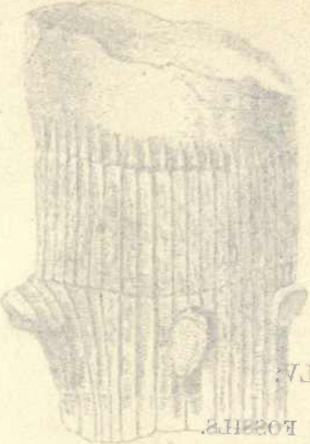
Bathonian (Great Oolite).—This consists of a series of thin-bedded limestones and clays, which have been divided into three well-marked sub-stages:—

Bathonian	(*c*)	Cornbrash.
	(*b*)	Forest Marble.
	(*a*)	Great Oolite.

At the base of the Great Oolite there is what is known as the *Stonesfield Slate*, which is of peculiar geological interest. It is developed in parts of Gloucestershire and Oxfordshire, and contains a remarkable mixture of marine and estuarine forms mingled with the remains of land plants and animals. Among the most prevalent fossils are the following genera:—

Brachiopods	include	*Terebratula* and *Rhynchonella* (Plate XLIV.).
Lamellibranchs	,,	*Gervillia*, *Ostrea*, *Lima*, *Pecten*, *Astarte*, *Modiola*, and *Trigonia*.
Gasteropods	,,	*Natica*, *Patella*, and *Trochus*.
Cephalopods	,,	*Ammonites gracilis* and *Belemnites fusiformis*.
Fishes	,,	*Ceratodus*, *Hybodus*, and *Ganodus*.
Reptiles	,,	*Plesiosaurus*, *Cetiosaurus*, *Teleosaurus*, and *Megalosaurus*.
Mammalia	,,	the marsupials *Amphilestes* and *Phascolotherium*.
Plants	,,	*Pecopteris*, *Tæniopteris*, and *Sphenopteris*.

Crustaceans and insects are numerous, the latter including many examples of beetles, moths, butterflies, dragon-flies, etc.



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LOWER JURASSIC FOSSILS.

(*Inferior Oolite.*)

PLATE XLV.

LOWER JURASSIC FOSSILS.

(*Inferior Oolite.*)

1. *Equisetites columnaris* (Brong.). Inferior Oolite shale. Gristhorpe, etc., Yorkshire.
2. *Pterophyllum.* Inferior Oolite shale. Yorkshire coast.
3. *Pterophyllum comptum* (L. & H.). Inferior Oolite shale. Yorkshire.
4. *Tœniopteris vittata* (Brong.). Inferior Oolite shale. Whitby, Gristhorpe, etc.

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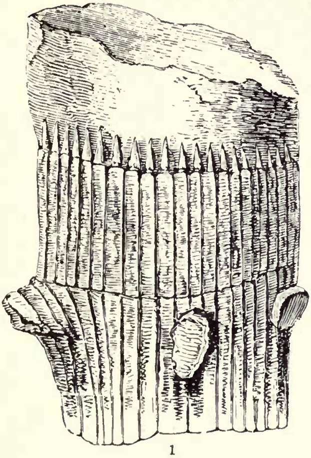
[Plate XLV.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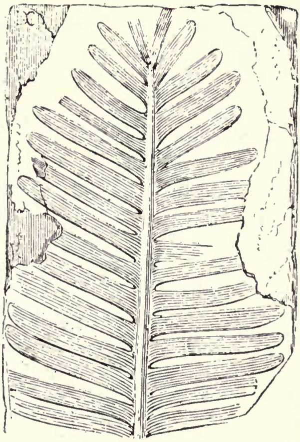
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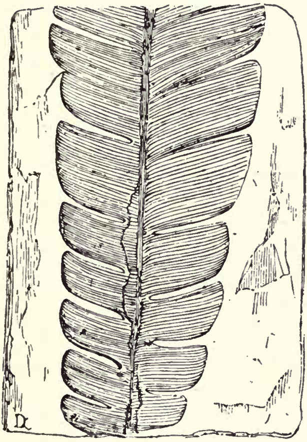

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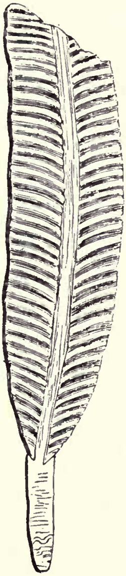
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Lower Jurassic Fossils.

(*Inferior Oolite.*)

The *Great Oolite* proper was laid down in a shallow sea swarming with a prolific marine life, which included corals, bryozoans, sea-urchins, and starfish, all the inhabitants of clear sea-water; also:—

Brachiopods,	including	*Rhynchonella, Terebratula, Magellania,* and *Crania.*
Lamellibranchs,	,,	*Pecten, Lima, Ostrea, Avicula, Astarte, Modiola, Pholadomya, Trigonia, Cardium, Arca, etc.*
Gasteropods,	,,	*Nerita, Nerinœa, Patella, etc.*
Cephalopods,	,,	*Ammonites arbustigerus, A. gracilis, A. subcontractus, etc.*
Reptilians,	,,	most of those in the Stonesfield Slate.

The *Forest Marble* attains a thickness of several hundred feet in Dorset, but thins out rapidly going northward. It is chiefly notable for its echinoderms, which include, among other species, the distinctive form *Apiocrinus elegans.*

The *Cornbrash* receives its name from the abundant crops of grain which are produced on its soils. It is a thin bed of earthy limestone varying from 5 to 40 feet thick, which, notwithstanding its insignificant dimensions that rarely exceed 20 feet, runs across the country from Devonshire to Yorkshire, and is therefore the most persistent member of the Lower Oolite Series or even of the Jurassic System.

Among the characteristic fossils of the Cornbrash are *Echinobrissus clunicularis* (Plate XLIV.), *Hinnites gradus, Cardium latum,* and the Cephalopods, *Ammonites discors* and *A. macrocephalus.*

Middle Oolite.

This division of the Jurassic System comprises two groups of beds:—

Middle Oolite
- 2. Corallian.
- 1. Oxfordian
  - (*b*) Oxford Clay.
  - (*a*) Callovian.

Oxfordian.—This stage consists of two sub-stages, namely, the *Callovian* or *Kellaways Rock,* which is the lower sub-stage, and the Oxford Clay, the upper sub-stage.

The Callovian, also known as *Kellaways Rock,* which derives its name from the village of Kellaways, in Wiltshire, where this important subdivision was first described, is a calcareous sandstone, varying from 5 to 80 feet thick. It can be traced from Wiltshire to Lincolnshire, and northward into Yorkshire, where it is well developed.

The Callovian is chiefly notable for its fish remains, of which over

200 species have been identified; of these about one-third are found in the underlying Jurassic rocks, and about one-third pass upward into the overlying beds.

The fauna indicates a revival of the estuarine conditions which characterised the Estuarine Series of the northern counties in the Lower Oolite times; and contains, besides the fishes mentioned above, a considerable number of molluscs, among which we have *Ammonites*, *Belemnites*, the widely distributed *Gryphæa bilobata*, *Ostrea*, *Lima*, *Avicula*, *Lucina*, *Trigonia complanata*, *Cerithium abbreviatum*, and *Pleurotoma arenosa*.

The characteristic Ammonite of Kellaways Rock is *Ammonites calloviensis*; hence the name *Callovian* by which this zone is so commonly known outside the British Isles.

Oxford Clay.—This great argillaceous deposit ranges throughout England from the coast of Dorset to Scarborough on the Yorkshire coast. It consists essentially of stiff clays and bituminous shales, and varies from 170 to 600 feet thick.

The muddy conditions of deposition of these sediments were obviously unfavourable for the growth of corals and bryozoans, which are rare, as also are echinoderms, which usually frequent clear water. Brachiopods and Gasteropods are not common, but the shallow-water Lamellibranchs which congregate in shell-banks are very abundant, and include *Gryphæa dilatata*, *Ostrea*, *Lima*, *Pecten*, *Avicula*, *Astarte*, *Trigonia*, *etc.*

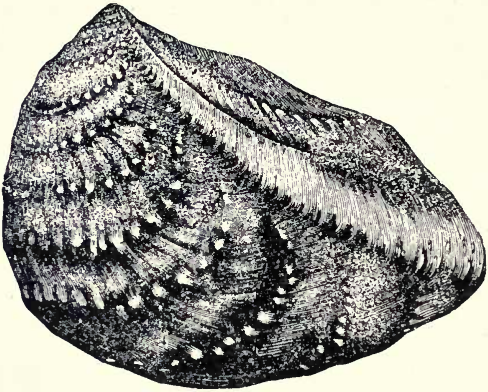
Ammonites are numerous and *Belemnites* not uncommon, of the latter *B. Oweni* being the best known. The reptilian genera *Ichthyosaurus*, *Plesiosaurus*, and *Megalosaurus* are also present. Crustaceans and insects also occur, but plant remains are comparatively scarce.

Palæontologically the Oxfordian Series is divided into four Ammonite zones:—

4. Zone of *Ammonites cordatus.*
3. ,, ,, *Lamberti.*
2. ,, ,, *Jason.*
1. ,, ,, *calloviensis.*

The Corallian.—This is the upper division of the Middle Oolite. It consists mainly of shelly and oolitic limestones and calcareous sandstones, and is chiefly characterised by the presence of many corals. It extends from the coast of Dorset to Yorkshire. In some parts of Wiltshire the upper limestones have been replaced by valuable deposits of ironstone.

The corals mostly belong to the reef-building kinds, and, notably in Yorkshire, are found forming coral reefs in the positions in which they grew.



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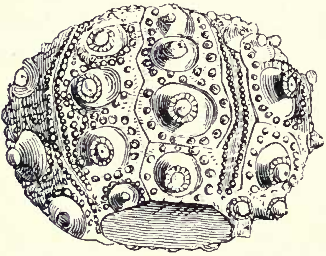

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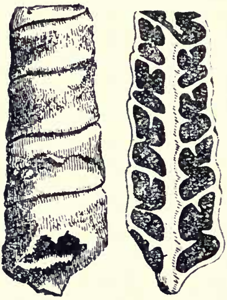

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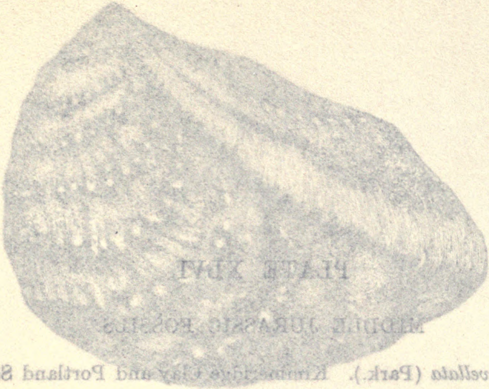
MIDDLE JURASSIC FOSSILS.

PLATE XLVI.

MIDDLE JURASSIC FOSSILS.

1. *Trigonia clavellata* (Park.). Kimmeridge Clay and Portland Sand. Weymouth, Swindon, etc.
2. *Ostrea gregaria* (Sow.). Corallian beds. Yorkshire, Wiltshire, Cambridgeshire.
3. *Nerinœa Goodhallii* (Sow.). Corallian beds. Dorsetshire (Osmington, etc.).
4. *Gryphœa dilatata* (Sow.). Corallian and Oxfordian rocks. Wilts, Yorkshire, Oxfordshire, etc.
5. *Littorina muricata* (Sow.). Corallian beds. Wiltshire, Yorkshire, Cambridgeshire.
6. *Cidaris florigemma* (Phill.). Coral Rag. Calne, Yorkshire, etc.



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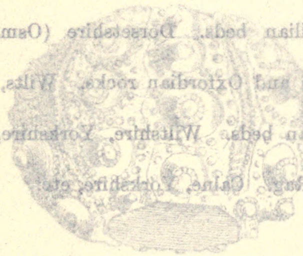

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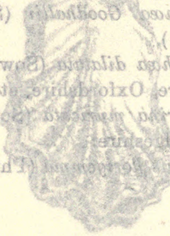

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MIDDLE JURASSIC FOSSILS.

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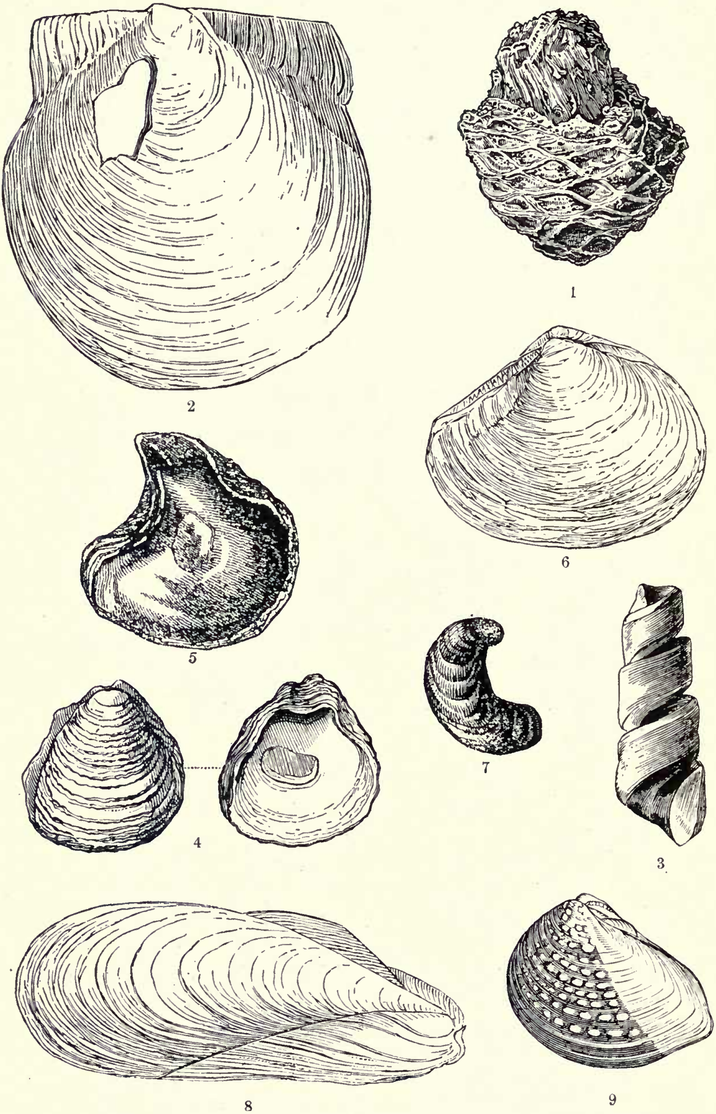


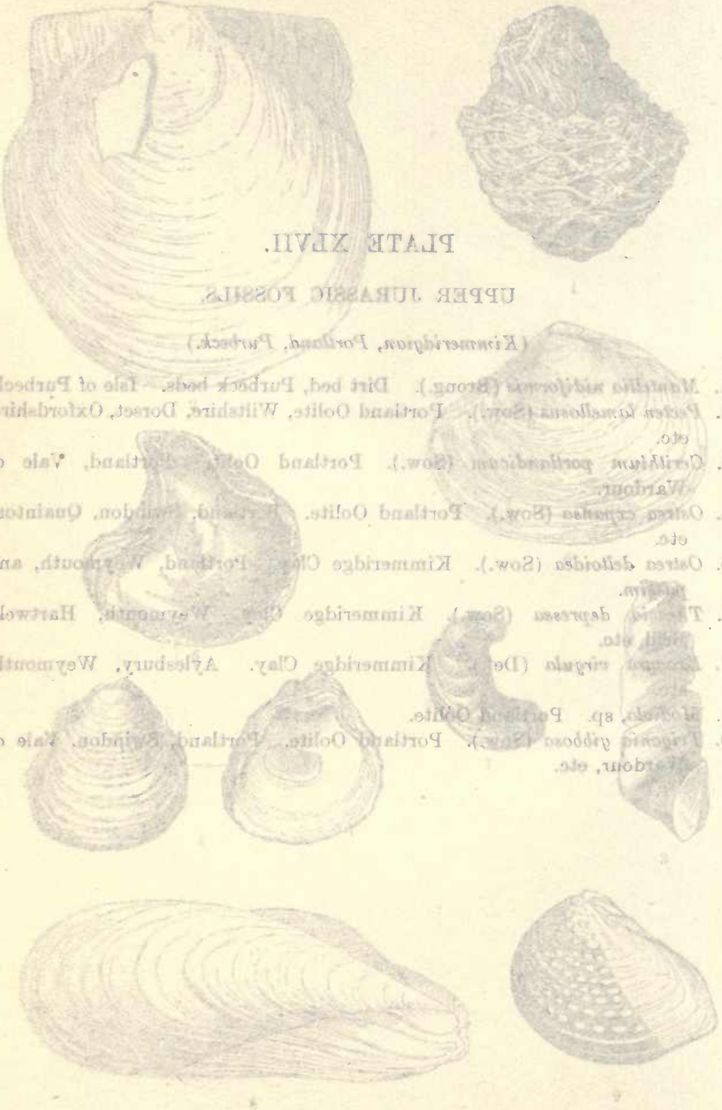
UPPER JURASSIC FOSSILS.
(*Kimmeridgian, Portland, Purbeck.*)

PLATE XLVII.

UPPER JURASSIC FOSSILS.

(*Kimmeridgian, Portland, Purbeck.*)

1. *Mantellia nidiformis* (Brong.). Dirt bed, Purbeck beds. Isle of Purbeck
2. *Pecten lamellosus* (Sow.). Portland Oolite, Wiltshire, Dorset, Oxfordshire, etc.
3. *Cerithium portlandicum* (Sow.). Portland Oolite. Portland, Vale of Wardour.
4. *Ostrea expansa* (Sow.). Portland Oolite. Portland, Swindon, Quainton, etc.
5. *Ostrea deltoidea* (Sow.). Kimmeridge Clay. Portland, Weymouth, and *passim.*
6. *Thracia depressa* (Sow.). Kimmeridge Clay. Weymouth, Hartwell, Brill, etc.
7. *Exogyra virgula* (Def.). Kimmeridge Clay. Aylesbury, Weymouth, etc.
8. *Modiola*, sp. Portland Oolite.
9. *Trigonia gibbosa* (Sow.). Portland Oolite. Portland, Swindon, Vale of Wardour, etc.



UPPER JURASSIC FOSSILS.
(*Kimmeridgian, Portland, Purbeck.*)

Sea-urchins are numerous and include *Cidaris*, *Hemicidaris intermedia*, and *Pygaster umbrella*. Among the Lamellibranchs, *Gryphæa*, *Ostrea*, *Lima*, *Pecten*, and *Avicula* are plentiful; also *Trigonia clavellata*, which is characteristic. *Ostrea gregaria* occurs in great numbers (Plate XLVI., fig. 2).

The principal Ammonites are *A. perarmatus* and *A. plicatilis*, both of zonal importance:—

2. Zone of *Ammonites plicatilis*—Upper Corallian.
1. ,, ,, *perarmatus*—Lower Corallian.

Upper Oolite.

The three main subdivisions of the Upper Oolite are:—

3. Purbeckian—Limestone.
2. Portlandian—Limestone.
1. Kimeridgian—Clays.

The Kimeridgian.—The Kimeridge Clay is one of the most persistent subdivisions of the Jurassic in England. It usually consists of dark-grey or black shaly clays, with frequent layers of septarian concretions. Occasionally the shales are calcareous and pass into bands of limestone. In the north of Scotland, on the east coast of Sutherlandshire, the beds are mostly sands, grits, and limestones.

The Kimeridge Clay is well developed around Kimeridge on the coast of Dorset, whence it extends northward to the Yorkshire coast. The thickness varies from 1200 feet in the South-West District to 100 feet in Oxfordshire.

The Kimeridgian is everywhere richly fossiliferous, and was obviously laid down in muddy seas swarming with the peculiar marine life of shallow waters. Hence corals and echinoderms are rare, and brachiopods are not common; but Lamellibranchs and Cephalopods are numerous, the former being represented by the characteristic species *Exogyra virgula* (Plate XLVII., fig. 7), *Ostrea deltoidea* (Plate XLVII., fig. 5), and *Astarte supracorallina*; and the latter by *Ammonites alternans*, *A. mutabilis*, and *A. biplex*.

The seas and estuaries still swarmed with reptilians, which included the marine plesiosaurs *Plesiosaurus* and *Pliosaurus*. The unwieldy and uncouth deinosaurs *Cetiosaurus*, *Gigantosaurus*, *Camptosaurus* (*Iguanodon*), and *Megalosaurus* still herded in the marshy lands, while the crocodiles *Teleosaurus*, *Steneosaurus*, and others frequented the estuaries and deltas. The fish-like ichthyosaurs still inhabited the neighbouring seas, and the flying pterosaur *Pterodactylus* continued to dominate the air.

Palæontologically the Kimeridgian is divided into two Ammonite zones :—

2. Zone of *Ammonites biplex* = Upper Kimeridgian.
1. ,, ,, *alternans* = Lower Kimeridgian.

The Portlandian.—This series takes its name from the Isle of Portland, where it is typically developed. It follows the Kimeridgian conformably, but has a narrower surface exposure, this, in the south of England, being mainly due to the overlap of the Upper Cretaceous. Further north from Bedfordshire to Norfolk, and in Yorkshire, no Portlandian beds are known, which may be due either to local uplift after the Kimeridgian period or to denudation before the Cretaceous.

The Portlandian consists typically of marine limestones and sands, and the former encloses a rich fauna.

Corals are rare, and represented by one species, *Isastræa oblonga.* Brachiopods are also scarce. The most abundant fossils are Lamellibranchs, Gasteropods, and Cephalopods. In this formation the Ammonites attain a remarkable size.

Among the best-known molluscs in the Portlandian are the following :—

Lamellibranchs—*Trigonia gibbosa* (Plate XLVII., fig. 9).
Gasteropods—*Cerithium portlandicum* (Plate XLVII., fig. 3).
Cephalopods—*Ammonites giganteus.*

Fishes are represented by the persistent *Hybodus* and *Gyrodus,* while most of the reptilians of the Middle Jurassic are also present.

In the Isle of Portland and South-West England the Portlandian presents two distinct subdivisions, namely :—

2. Portland Stone—Upper Portlandian.
1. Portland Sand—Lower Portlandian.

The *Portland Sand* consists of yellow, brown, and greenish sands, with occasional layers of clay and limestone ; and the *Portland Stone,* of white shelly or oolitic limestone, with layers and nodules of chert.

The Purbeckian.—This series is typically developed in the Isle of Purbeck and in South-West England, and generally its distribution is coextensive with that of the underlying Portlandian with which it is everywhere closely associated. In most places it follows the Portlandian quite conformably, but in some localities there is evidence of uplift at the close of that stage whereby some portions of the sea-floor became dry land and other portions shallow estuaries. This uplift by introducing terrestrial and estuarine conditions caused the migration from these areas of the marine life and reptilian forms which characterised the preceding Jurassic seas and shores.

The Purbeckian consists mainly of shales, marls, and limestones, with occasional beds of dark sandy clays containing much carbonaceous matter. These clays probably represent the soils of old land surfaces. They are locally called *Dirt Beds*, and in some places contain the trunks of cycads and conifers.

There is also a marine bed intercalated in the series composed almost entirely of the shells of the oyster *Ostrea distorta*. These shells impart a rough surface to the outcrops of the bed, which is in consequence frequently called the *Cinder Bed*.

Among the freshwater shells found in the Purbeckian Series, *Unio*, *Paludina*, *Physa*, and *Limnœa* are abundant. Insects are also plentiful and often beautifully preserved. Fishes are numerous, but reptiles are not common, and the forms present are mostly of the crocodilian type.

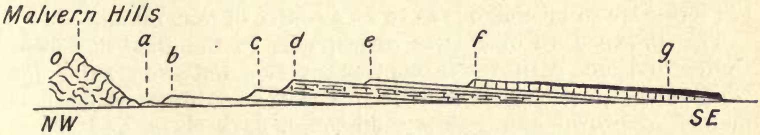


Fig. 216a.—Showing arrangement of Mesozoic formations from Malvern Hills to coast of Essex.

(*o*) Pre-Cambrian gneiss.
(*a*) Trias.
(*b*) and (*c*) Lias.
(*d*) and (*e*) Oolites of Cotteswold Hills.
(*f*) Chalk of Chiltern Hills.
(*g*) Eocene of Essex.

The Purbeckian is chiefly celebrated for its mammalian remains, which are found at Durleston Bay in a stratum five inches thick in the middle of the series. The mammals belong to the marsupial order and include the genera *Plagiaulax* and *Triconodon*.

Jurassic in other Countries.

France.—Lithologically and palæontologically, the Jurassic in this region does not differ greatly from that of England except in the Mediterranean Province. The subdivisions recognised in France are as follow:—

Oolite
9. Portlandian.
8. Kimeridgian.
7. Corallian.
6. Oxfordian.
5. Bathonian.
4. Bajocian.

Lias
- 3. Toarcian.
- 2. Liassian.
- 1. Sinemurian.

Infra-Lias — Hettangian—Lies conformably on the *Avicula contorta* zone of the Rhætic.

Germany.— The subdivisions of the Jurassic recognised in North-West Germany are :—

3. Upper or White Jura (=Malm).
2. Middle or Brown Jura (=Dogger).
1. Lower or Black Jura (=Lias).

The *Black Jura* is essentially an argillaceous formation and closely resembles the English Lias. It derives its name from the prevailing black colour of the shales which in the upper part of the series are so bituminous as to be a source of mineral oil.

The *Brown Jura* or *Dogger* corresponds to the English Lower Oolite division, with the exception of the *Callovian* sub-stage which German geologists include in the White Jura. It consists mainly of brown and yellow sandstones, dark clays, and shales with bands of oolitic ironstone.

The *Malm* or *White Jura* receives its name from the prevailing colour of the rocks, which consist mainly of dolomitic limestones and marls.

The Jurassic rocks in Germany exhibit a close faunal relationship to the Jurassic of England, a correspondence which doubtless arises from the circumstance that England and Germany, in common with North France, lie in the *Central European Biological Province*, to which reference will be made later.

Russia.—Jurassic rocks cover a larger area in Russia than in any other part of Europe notwithstanding that the Lias and the Lower Oolite—that is, all below the Callovian—are absent. From this it would appear that Russia was dry land during the lower half of the Jurassic period.

The Jurassic fauna of Russia does not bear a close resemblance to that of England or Germany, which may arise from the fact that the Jurassic rocks of that region were deposited in a more northerly biological province or zone.

India.—There are two types of Jurassic rocks in India, namely, the *Marine* and the *Continental*.

The Marine type has an extraordinary development in Northern India, where it is represented by two facies in point of age, the *Alpine* and *Coastal*, the former comprising the Lower Jurassic rocks, the latter the Upper Jurassic.

The Alpine facies consists of massive beds of limestone which are developed on a vast scale in Baluchistan, in the Inner Himalayas, and in Tibet. The Coastal facies is met with in the Cutch, and Salt Range in the Punjab.

The succession of the Alpine Jurassic is interrupted by a break at the close of the Callovian stage arising from uplift; and deposition did not again begin in this region until about the end of the Jurassic or beginning of the Cretaceous period. The Liassic and Lower Oolitic rocks are well represented; and the principal Ammonite zones of Central Europe and England have been identified in the black limestones of Baluchistan, in which they follow the same chronological succession.

In the Coastal facies the Lias and Lower Oolite are absent, showing that, at the time a sea-floor existed in the North Himalayan and Tibetan areas, dry land occupied the Cutch. When deposition began in the Coastal area, the Alpine area emerged from the sea.

In the matter of age, the Jurassic rocks of the North Himalayan and Tibetan regions exhibit a singular contrast with those of the Cutch, the stages present in the coastal region being absent in the extra-peninsular, and the converse. Obviously subsidence in the one region was compensated by uplift in the other.

The *Continental type* of the Jurassic System of India is represented by the Upper Gondwana, which consists mainly of sandstones and shales with coal-seams and bands of limestone. In the Rajmahal Hills the rocks are intercalated with massive sheets of basalt.

The Rajmahal Shales contain a rich fossil flora which includes an abundance of ferns and cycads, the latter being represented by *Ptilophyllium*, and the former by *Tæniopteris* and *Dicksonites*.

During the Jurassic period the Himalayan region of Northern India was a sea-floor; and so far as the available evidence will permit us to judge, it would appear that the continent from which the Jurassic sediments were derived lay to the south and south-east. This continent, of which the Peninsular area formed a part, was the Gondwana Land of Indian geologists.

North America.—Jurassic rocks are not found in the Eastern States, but are well developed in California, Sierra Nevada, and Alaska; and also in the States of Wyoming, Utah, Dakota, and Colorado, where they have yielded a remarkable group of deinosaurs, tortoises, pterodactyles, crocodiles, and lizards, the latter including some forms related to the living *tuatara* (*Sphenodon punctatum*) of New Zealand. The deinosaurs were herbivorous, and among the principal genera distinguished by Marsh are *Atlantosaurus*, *Brontosaurus*, and *Stegosaurus*.

Associated with these reptilian remains, there have also been found many genera of small marsupial mammals, including the genera *Allodon*, *Docodon*, *Tinodon*, and many others.

In California the thickness of the Jurassic rocks is about 2000 feet, part of which is volcanic tuff; and in Nevada, 5000 or 6000 feet, the upper 4000 feet of which are slates, the remaining lower beds being limestones.

In this State the Jurassic rocks are sharply folded and frequently much metamorphosed. The fauna of this region, so far as it has been studied, shows a relationship to that of the Central European Biological Province. Generally speaking, the Jurassic System plays a subordinate part in the geological structure of North America, the greater portion of which was dry land from the close of the Triassic till the Cretaceous.

Australasia.—Jurassic rocks have been identified in Borneo and New Guinea, whence they extend southward to Queensland, New South Wales, Victoria, South Australia, Western Australia, and New Zealand.

In the Australian Continent the rocks for the most part consist of sandstones (greywackes), shales, and conglomerates of the continental facies. They are distinguished by the presence of fossil plants, reptilian and fish remains.

A characteristic and widespread fern is *Tæniopteris daintreei*; but the succession of the Jurassic rocks has not yet been worked out in detail.

In New Zealand the Jurassic rocks consist of two types, the Coastal and Alpine. The rocks of the coastal type contain thin seams of bituminous coal and occasional bands of estuarine sandstones and shales. Plant remains are abundant and include *Tæniopteris*, *Pecopteris*, and *Sphenopteris*. The molluscs are mostly those found in shallow seas and estuaries. They include *Pecten*, *Lima*, *Avicula*, *Ostrea*, *Pinna*, *Modiola*, *Ammonites*, and *Belemnites*.

The Jurassic rocks of the Alpine type are mainly developed in the Alpine Chain, where they attain a thickness exceeding 10,000 feet. They consist of a vast pile of alternating greywackes and shales of the *Flysch* facies, and, so far as known, are devoid of all fossils. They appear to have been formed in the delta of a river which may have drained the southern portion of the ancient Gondwana Land.

Calcareous rocks are conspicuously absent in the Jurassic System, as developed in Australia and New Zealand.

Zonal Distribution of Faunas.—As the faunas become more highly organised and differentiated, they are increasingly subject to the influences of climatic conditions; and the tendency of progressive biological development is to bring into existence forms adapted to their peculiar environment.

There is not much evidence until we reach the Jurassic period, that the distribution of the marine inhabitants was influenced by climatic conditions. But in the faunas of the marine limestones and marls of this period there is abundant evidence that the climatic or faunal zones, which are so characteristic of the present time, had already been well established.

The detailed study of the Jurassic faunas of Europe appears to show that they may be divided into three zones encircling the globe in a direction parallel to the equator.

In geological times later than the Jurassic, the faunas in similar climatic zones show a biological relationship in the corresponding latitudes in each hemisphere.

Jurassic Biological Zones or Provinces.—In Continental Europe where the Jurassic faunas have been studied more closely than elsewhere, Neumayr has distinguished three Jurassic marine provinces characterised by different faunas:—

(1) *The Mediterranean Province*, which includes the deposits of the Balkan Peninsula, Carpathians, Cevennes, Italy, Spain, Crimea, Caucasus, Asia Minor, and Further India.
(2) *The Middle European Province*, which includes the extra-Alpine Jurassic of France, Germany, the Jurassic of England, North-West Spain, Portugal, the Baltic Region, Japan, and California.
(3) *The Russian or Boreal Province*, which includes the Jurassic rocks of Central and Northern Russia, Nova Zembla, Spitzbergen, Greenland, and Alaska.

All three facies occupy broad belts or zones passing round the globe in the direction of the parallels of latitude. These *isozoic zones* coincide with the climatic zones:—

The *Mediterranean Province* = the *Alpine, Equatorial*, or *Tropical Zone.*
The *Middle European Province* = the *Temperate Zone.*
The *Russian or Boreal Province* = the *Arctic* or *Boreal Zone.*

The Jurassic faunas of the Southern Hemisphere occur in the same isozoic zones as in the Northern. For example, the Jurassic faunas of South Australia, New Zealand, Cape Colony, Chile, Bolivia, Peru, and Argentine, exhibit a striking resemblance to the Jurassic faunas of England and Swabia.

The *Equatorial Zone* is characterised by the extraordinary development of Ammonites of the genera *Phylloceras*, *Lytoceras*, and *Simoceras*; and of the brachiopods, *Terebratula diphya* is peculiar to this province.

In the Temperate Zone *Phylloceras* and *Lytoceras* are not common, while *Harpoceras*, *Peltoceras*, *Aspidoceras*, and *Oppelia* are very abundant. Coral reefs are prominent and frequently of great extent and thickness.

In the *Boreal Zone* the Ammonite genera *Harpoceras*, *Lytoceras*, and *Phylloceras* are entirely absent, and coral reefs are unknown. On the other hand, an Ammonoid *Cardioceras* and the Lamellibranch *Aucella* are characteristic and widespread.

CHAPTER XXX.

CRETACEOUS SYSTEM.

THE Cretaceous is the youngest of the three great systems into which the Mesozoic is divided. It received its name in England from its most important member the *Chalk*, for which the Latin name is *creta*.

The Cretaceous System is world-wide in distribution, and embraces a considerable variety of sandy, clayey, and calcareous deposits.

At the close of the Jurassic, the form of the great continents was already clearly outlined; hence the Cretaceous sediments were laid down for the most part in seas marginal to the existing continents, or in land-locked estuaries and basins to which the sea had free access. As a result of this marginal distribution, the deposits of this period are frequently covered over to a considerable extent with the succeeding Tertiary formations, which were also laid down as marginal sheets mantling round the shores of the continents and larger islands.

Rocks.—The prevailing rocks are sands, clays, shales, and limestones, but the deposits frequently exhibit considerable local variations due to differences in the conditions of deposition. Even the *Chalk*, which is so prominent and important in England, North France, Belgium, Baltic area, and North America, is absent in Central Germany, Alps, Africa, and Australia.

The lower members of the system in North-West Europe are frequently sandy beds of terrestrial and estuarine origin with plant remains and seams of coal. Following these come alternating sandy and clayey deposits of marine origin frequently containing lines of septarian concretions; and in their turn these are succeeded by chalk and other calcareous beds which in many regions close the succession, but in others are followed by estuarine and terrestrial deposits with coal-seams.

The sandy beds of both hemispheres are frequently dark green in colour, due to the presence of glauconitic grains.

In both hemispheres the Upper Cretaceous seas advanced over the low-lying maritime lands of all the continents, and this unprecedented transgression was so rapid and universal that the Upper Cretaceous sediments extend far beyond the limits of the Lower Cretaceous, and rest on the worn-down surfaces of the older formations on which they trespass in some regions for thousands of square miles.

At the close of the Cretaceous, the long era of quietude and immunity from volcanic disturbance was broken by the revival of eruptions on a gigantic scale; and since that date volcanic activity of a more or less intense kind has been in evidence in some part of the globe up to the present day.

From the above it would appear that the Cretaceous deposits were laid down on a slowly sinking sea-floor until the middle of the period, when a sudden invasion of the sea took place. Thereafter, subsidence continued in many regions until the close of the Chalk, when the uplift began which eventually led to the deposition of the estuarine and terrestrial deposits of the uppermost beds of the Cretaceous.

Distribution.—The Cretaceous is found in all the great continents. It is one of the most extensively developed of all the rock-systems, and in some regions covers hundreds of thousands of square miles in one continuous sheet.

In Europe the Cretaceous presents two distinct palæontological facies, the Central European and Mediterranean. The Central European is well developed in England, North France, Belgium, Hanover, Westphalia, Saxony, Bohemia, and Baltic area; and the Mediterranean type on both sides of that basin, in Portugal, Spain, South France, Italy, Switzerland, Sicily, Greece, Carpathians, Morocco, Algiers, Tunis, Egypt, Syria, and Palestine.

The Mediterranean facies also stretches eastwards into Asia, and covers enormous tracts in Asia Minor, Persia, Arabia, Afghanistan, Baluchistan, Northern Himalayas, Tibet, and China.

The Cretaceous System is also present in Japan, Australia, New Zealand, Antarctic region near Graham's Land, Patagonia, Chile, Peru, Bolivia, United States, British Columbia, Alaska, and North Greenland. In the North American continent the northern and southern facies are as well marked as in Europe.

From this biological relationship we know that the Cretaceous sea extended from the Atlantic eastward through the Mediterranean area to Asia Minor, Persia, and India; and during the great transgression spread over the greater part of the desert area of North Africa. From the North Atlantic long arms of the Cretaceous sea extended through Germany and Baltic area to Northern Russia, reaching as far as Spitzbergen.

In the West Atlantic a broad prolongation of the sea stretched through the great Western Interior Basin of the Western States to Alaska, its waters laving the western foothills of the Rocky Mountains.

Flora.—The earliest Cretaceous flora is closely related to that of the Jurassic, and ferns, cycads, and conifers are still the dominant forms of vegetation ; but there was a remarkable change impending in the character of the land vegetation, and in the Upper Cretaceous we witness the world-wide appearance of the angiosperms, both monocotyledons and dicotyledons, which represent the highest forms of vegetation prevailing at the present time.

The advent of mammals and other highly organised vertebrates a full geological period ahead of the less delicately organised angiosperms is a biological puzzle the solution of which is not very obvious.

Fauna.—Many of the Jurassic genera appear in the Cretaceous together with new forms, and generally we may say that the fauna is stamped with a distinctly Mesozoic facies.

Foraminifera are exceedingly abundant as builders of chalk and other limestones, the most common genera being *Globigerina* and *Orbitolina*, the former characteristic of the true chalk of North-West Europe, the latter of the Alpine Cretaceous.

Calcareous sponges are common in the middle of the system, and siliceous sponges abound in the Chalk.

Corals of the reef-building type are rare. The few known genera of corals are such simple forms as *Parasmilia*, *Micrabacia*, and *Trochocyathus*, the last, well known in the Lower Tertiary.

Sea-urchins are numerous in the Chalk, the genera *Micraster*, *Holaster*, *Hemiaster*, *Echinobrissus*, and *Cidaris* being common. A few starfishes are known ; and crinoids are represented by the genus *Marsupites*. Polyzoans are common in the Calcareous division.

Brachiopods are abundant, and include *Terebratula*, *Terebratella* *Magas*, and *Rhynchonella*—all living genera—as well as the ancient *Crania*.

Molluscs are well represented. Among the common Lamellibranchs are *Inoceramus*, *Exogyra*, *Ostrea*, *Trigonia*, *Gervillia*, and *Spondylus*, as well as the curious genus *Hippurites*, which forms massive beds of limestone in the Alpine facies of Southern Europe. Of these *Inoceramus*, *Exogyra*, and *Hippurites* are distinctively Cretaceous, and the last is limited to this system.

The shell of *Inoceramus* is composed of aragonite built up of fibrous layers lying at right angles to the axis of the shell, which is consequently very fragile. Fragments of *Inoceramus* are common in the Chalk.

Of Gasteropods, the genera *Pleurotoma*, *Aporrhais*, *Rostellaria*, *Cerithium*, and *Fusus* are abundant.

Cephalopods swarmed in the Cretaceous seas, and are chiefly represented by Ammonites and Belemnites which make their last appearance. The Ammonite genera are specially characterised by the free-whorled (*Crioceras*), hooked (*Hamites*, fig. 217), and horn-shaped and turreted (*Turrilites*, fig. 218) forms, many of which possessed beautifully ornamented shells.

In the Upper Cretaceous the place of the true Belemnites is taken by *Belemnitella* and its sub-genus *Actinocamax.* The genus *Nautilus*, the most ancient and persistent of all Cephalopods, is represented by many species in the Upper Cretaceous, some of large size.

Fishes were common in the Cretaceous seas and rivers, and included many Teleosts (bony fishes) which became very plentiful towards the close of the period.

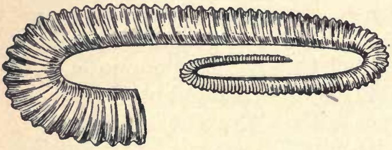


FIG. 217.—Hamites.

FIG. 218.—Turrilites.

The reptilians *Ichthyosaurus, Plesiosaurus,* and *Pterosaurus,* which dominated the vertebrate life of the Jurassic, are seen for the last time in the Cretaceous.

The huge deinosaurs reach their maximum development in this period, and disappear at its close. They are specially represented by *Iguanodon, Megalosaurus,* and *Cetiosaurus.* The gigantic pythonomorph or sea-serpent *Mosasaurus*, one of the extinct monsters of the Cretaceous seas, is estimated to have attained a length of 75 feet. The Cretaceous rocks of the Western States of North America have yielded a rich harvest of deinosaurs, pterosaurs, crocodilians, sea-saurians, turtles, and sea-serpents.

PLATE XLVIII.

To face page 408

CHARACTERISTIC CRETACEOUS AMMONITES.

PLATE XLVIII.

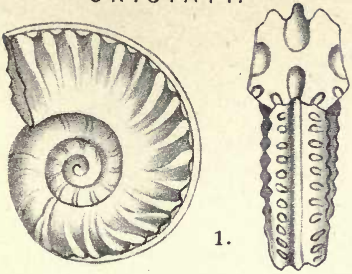
CHARACTERISTIC CRETACEOUS AMMONITES.

1. *Ammonites* (*Schlœnbachia*) *rostratus* (Sow.). Upper Greensand and Gault, Devizes and Folkestone.
   Group *Cristati*. Fam. *Schlœnbachia*.
2. *Ammonites* (*Hoplites*) *lautus* (Sow.). Gault and Upper Greensand.
   Group *Tuberculati*. Fam. *Schlœnbachia*.
3. *Ammonites clypeiformis* (Sow.). Upper Greensand.
   Group *Clypeiforme*. Fam.?
4. *Ammonites* (*Acanthoceras*) *Rothomagensis*. Chalk Marl and Lower Chalk.
   Group *Rothomagenses*. Fam. *Stephanoceratites*.
5. *Ammonites* (*Cosmoceras*) *Leopoldianus*. Neocomian.
   Group *Flexuosi*. Fam. *Stephanoceratites*.
6. *Ammonites* (*Hoplites*) *interruptus* (Sow.).
   Group *Dentati*. Fam. *Stephanoceratites*.
7. *Ammonites* (*Hoplites*) *Deshayesii* (Leym.). Upper Neocomian.
   Group *Angulicostati*. Fam.?
8. *Ammonites catillus* (Sow.). Upper Greensand.
   Group *Compressi*. Fam.?

PLATE XLVIII.

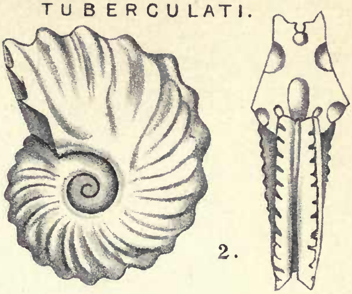
To face page 408.

CRISTATI.



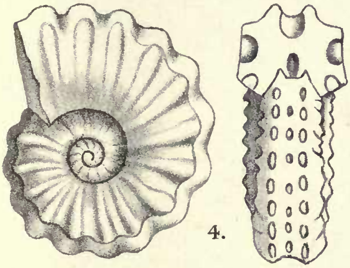
1.

TUBERCULATI.



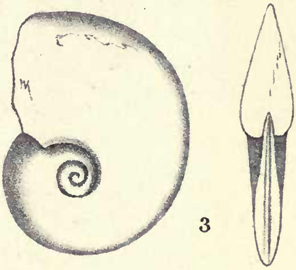
2.

ROTHOMAGENSES.



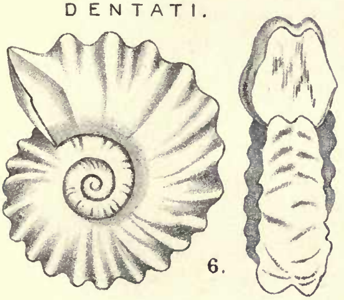
4.

CLYPEIFORMI.



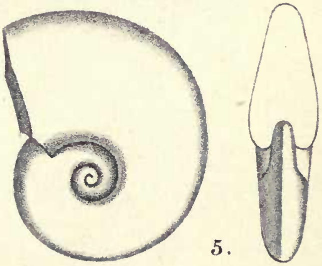
3

DENTATI.



6.

PLEXUOSI.



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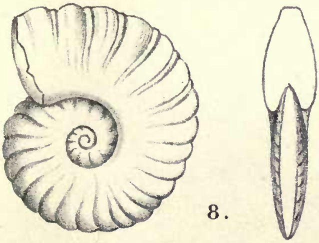
COMPRESSI.



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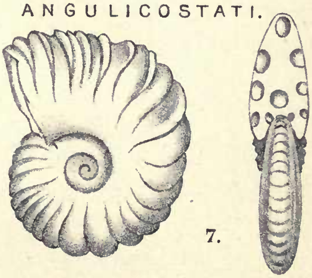
ANGULICOSTATI.



7.

McFarlane & Erskine, Lith. Edinr.

CHARACTERISTIC CRETACEOUS AMMONITES.

Perhaps no less remarkable than the deinosaurs are the toothed birds of the Cretaceous of Kansas, among the most interesting of which is *Ichthyornis victor*. The only bird remains found in the English Cretaceous are those of the genus *Enaliornis*.

With the deinosaurs, crocodiles, and other reptilians found in the Upper Cretaceous rocks of Dakota and Wyoming, there have been found numerous jaws and teeth of small marsupial mammals related to the Jurassic and Triassic forms.

Subdivisions.—The subdivisions of the Cretaceous System in England where the succession was first accurately determined, with the names of the corresponding subdivisions in North France,

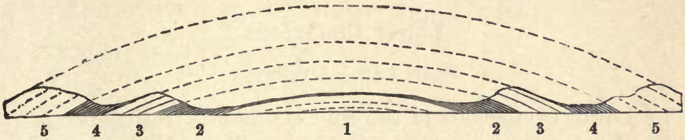


Fig. 219.—General section across Wealden.

1, Hastings Sand.
2, Weald Clay.
3, Lower Greensand.
4, Gault.
5, Upper Greensand and Chalk.

which are now commonly used as stage or time-names for the different groups of beds, are as follow :—

		England.	France.
Upper Cretaceous		Absent, . .	Danian.
	5. Chalk	Upper Chalk, .	Senonian.
		Middle Chalk, .	Turonian.
		Lower Chalk	Cenomanian.
	4. Upper Greensand, . .		
	3. Gault, ...		Albian.
Lower Cretaceous	2. Lower Greensand, . .		Aptian.
	1. Wealden	Weald Clay Hastings Sand	Neocomian.

The Cretaceous rocks of England occur in three distinct areas, namely, the Southern, Middle, and Northern. In the Southern District the deposits are mainly freshwater ; in the Middle District where the lower members are absent, marine ; and in the Northern District, marine.

In the Southern District they occupy almost the whole of the central portion of the Wealden Dome lying between the North and South Downs. They also appear in the Isle of Wight where they are tilted at high angles (fig. 219A), in the Isle of Purbeck, and near Weymouth, but these outcrops are subordinate in extent to that in the Weald, which is the largest and most important development of the Cretaceous in England or in the British Isles.

The Cretaceous rocks of the Middle District are chiefly developed in Bedfordshire and Cambridgeshire.

The Northern District extends from North Norfolk to Flamborough Head, and in this area the Cretaceous System is best displayed in Lincolnshire and Yorkshire.

The Cretaceous rocks fall into two great natural divisions: the Lower Cretaceous, well displayed in the Southern and Northern Districts; and the Upper Cretaceous, found in each of the three geographical areas referred to above.

Lower Cretaceous.

SOUTHERN DISTRICT.

The Lower Cretaceous of the south, which is freshwater, is quite unlike the Lower Cretaceous of the north, which is marine and palæontologically shows a relationship to the Lower Cretaceous of the Baltic area.

While freshwater basins existed in the south of England, and the Middle District formed dry land, a sea existed in the Northern District. But when subsidence took place, the southern sea invaded the freshwater basins, and encroached on the Middle District. Thereafter there was a continuous sea from south to north, and the fauna of the southern sea spread northward until it reached the Northern District.

Wealden (Neocomian).—This is a freshwater series which derives its name from the Weald of Sussex, Surrey, and Kent, where it is typically developed. It is overlain conformably by the Lower Greensand.

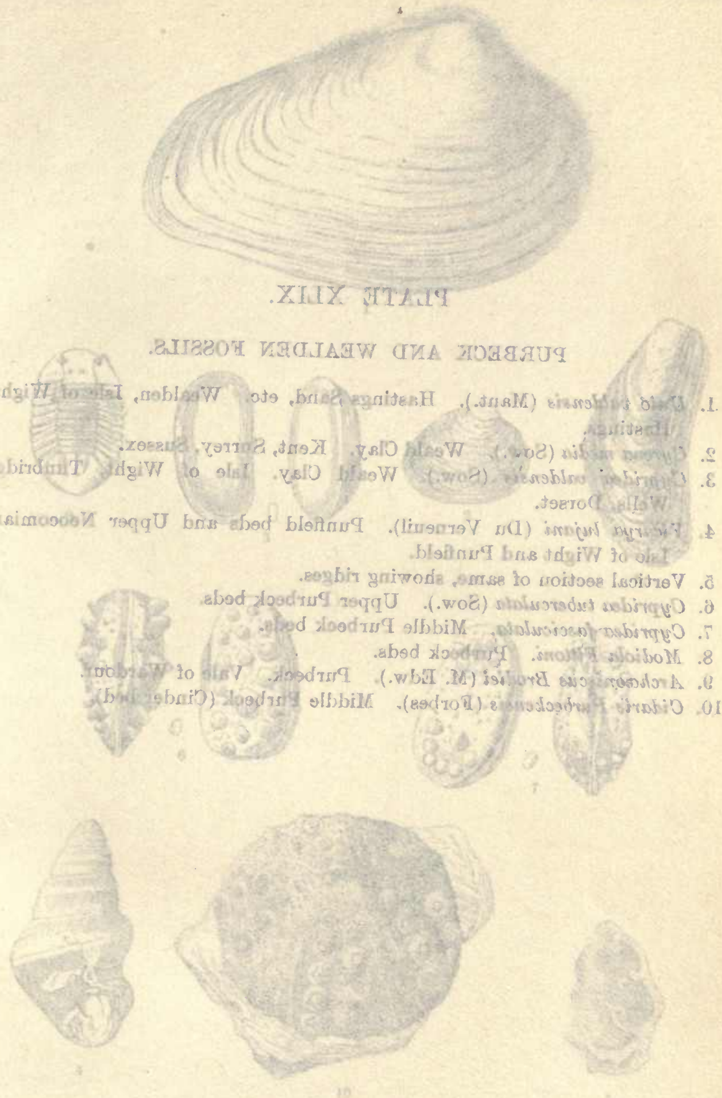
The Wealden comprises two main groups, namely :—

2. Weald Clay.
1. Hastings Sand.

The total thickness of the Wealden Series is over 2000 feet, of which the Weald Clay comprises about 1000 feet. The conditions of deposition were deltaic, and the sediments were apparently laid down during a period of slow but progressive subsidence.

The Wealden flora includes ferns, cycads, and conifers. Among the ferns are *Sphenopteris* and *Alethopteris*. The molluscs include the freshwater forms *Unio valdensis* (Plate XLIX., fig. 1), *Cyrena media* (Plate XLIX., fig. 2), *Viviparus fluviorum*, and a few littoral shells, including *Mytilus*, *Exogyra*, and *Ostrea*.

Among the fish we have *Lepidotus Mantelli*, a ganoid related



PURBECK AND WEALDEN FOSSILS.

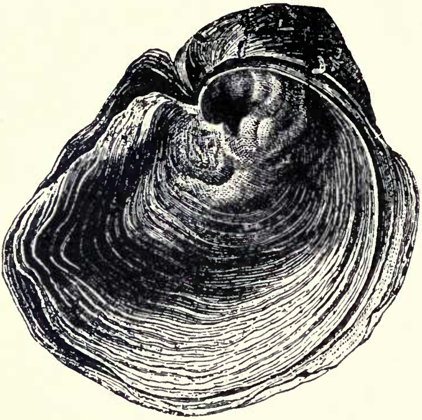
PLATE XLIX.

PURBECK AND WEALDEN FOSSILS.

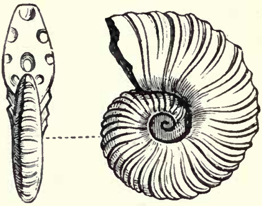
1. *Unio valdensis* (Mant.). Hastings Sand, etc. Wealden, Isle of Wight, Hastings.
2. *Cyrena media* (Sow.). Weald Clay. Kent, Surrey, Sussex.
3. *Cypridea valdensis* (Sow.). Weald Clay. Isle of Wight, Tunbridge Wells, Dorset.
4. *Vicarya lujani* (Du Verneuil). Punfield beds and Upper Neocomian. Isle of Wight and Punfield.
5. Vertical section of same, showing ridges.
6. *Cypridea tuberculata* (Sow.). Upper Purbeck beds.
7. *Cypridea fasciculata.* Middle Purbeck beds.
8. *Modiola Fittoni.* Purbeck beds.
9. *Archæoniscus Brodiei* (M. Edw.). Purbeck. Vale of Wardour.
10. *Cidaris Purbeckensis* (Forbes). Middle Purbeck (Cinder bed).

[PLATE XLIX.

PURBECK AND WEALDEN FOSSILS.



1



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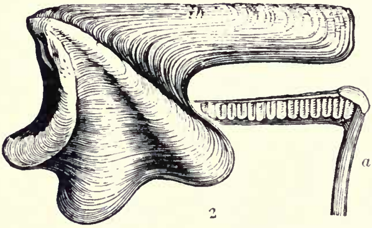

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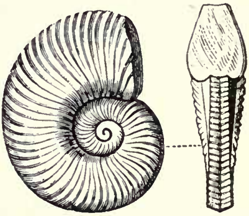

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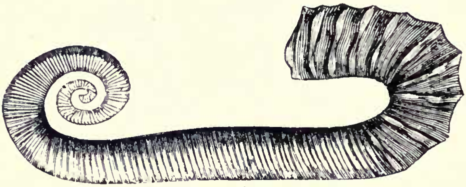

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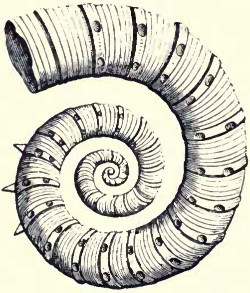

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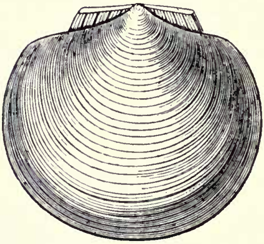


3

CRETACEOUS FOSSILS.
(*Neocomian.*)

PLATE L.

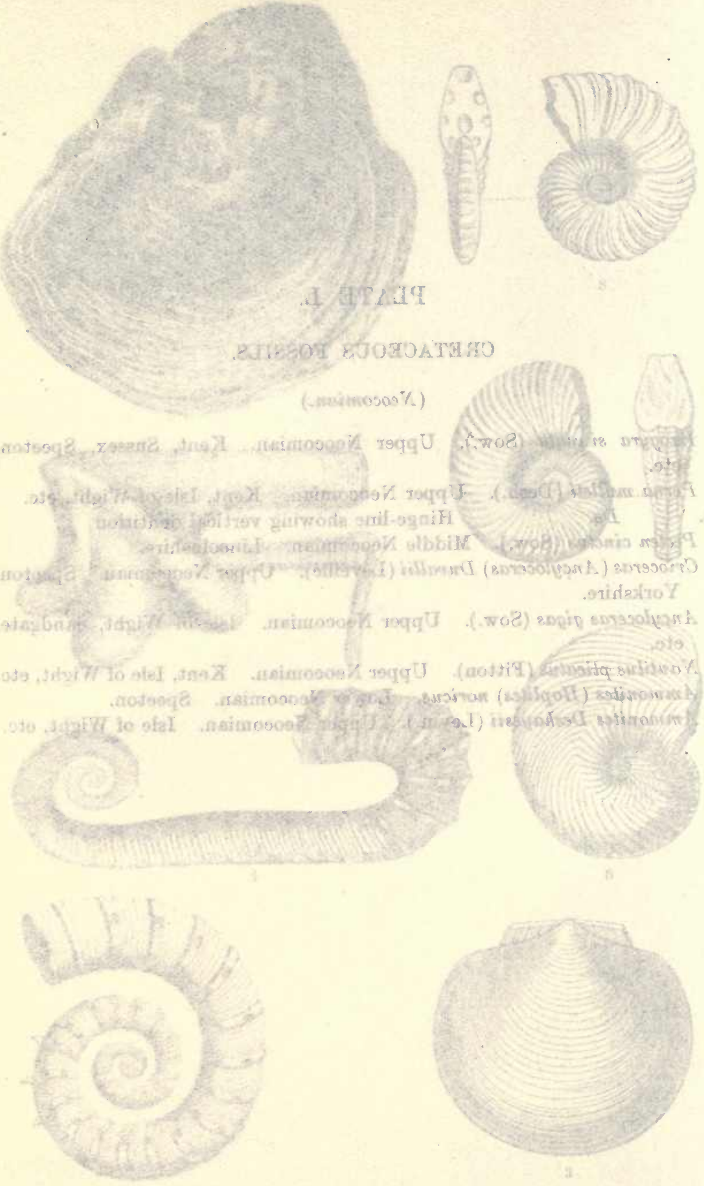
CRETACEOUS FOSSILS.

(*Neocomian.*)

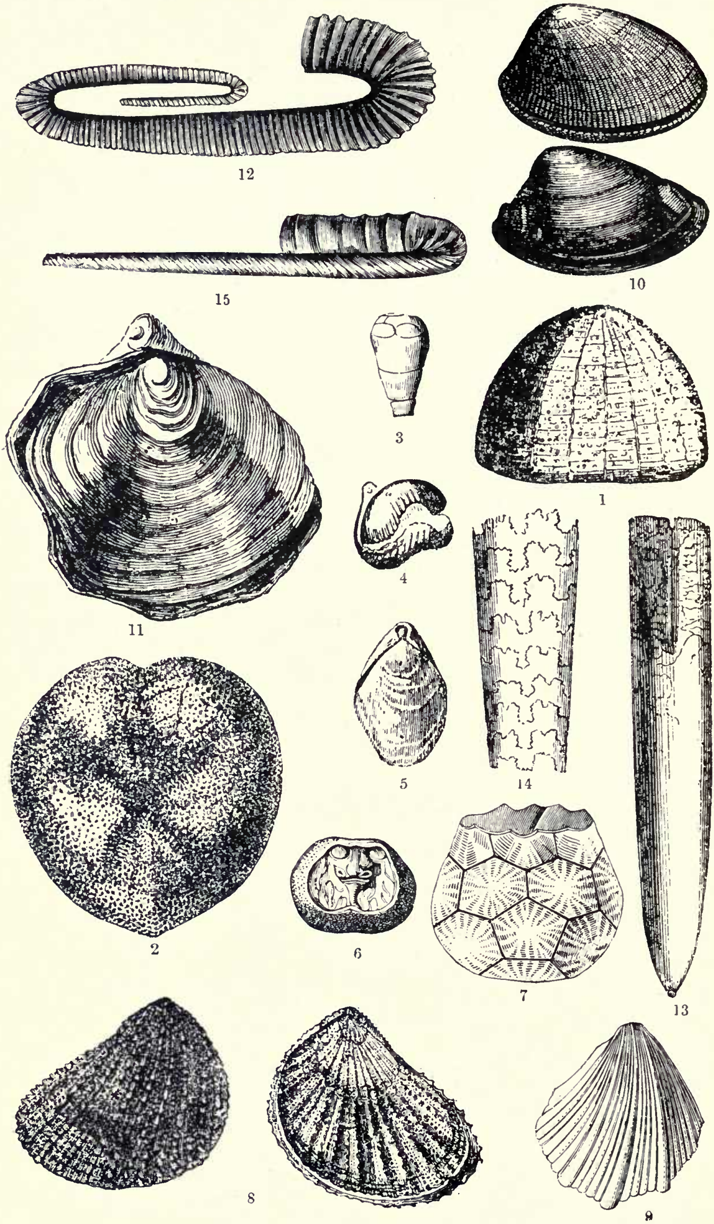
1. *Exogyra sinuata* (Sow.). Upper Neocomian. Kent, Sussex, Speeton, etc.
2. *Perna mulleti* (Desh.). Upper Neocomian. Kent, Isle of Wight, etc.

2*a*. *Do.* Hinge-line showing vertical dentition.

3. *Pecten cinctus* (Sow.). Middle Neocomian. Lincolnshire.
4. *Crioceras* (*Ancyloceras*) *Duvallii* (Léveillé). Upper Neocomian. Speeton, Yorkshire.
5. *Ancyloceras gigas* (Sow.). Upper Neocomian. Isle of Wight, Sandgate, etc.
6. *Nautilus plicatus* (Fitton). Upper Neocomian. Kent, Isle of Wight, etc.
7. *Ammonites* (*Hoplites*) *noricus*. Lower Neocomian. Speeton.
8. *Ammonites Deshayesii* (Leym.). Upper Neocomian. Isle of Wight, etc.



CRETACEOUS FOSSILS.
(Neocomian.)



Cretaceous Fossils.

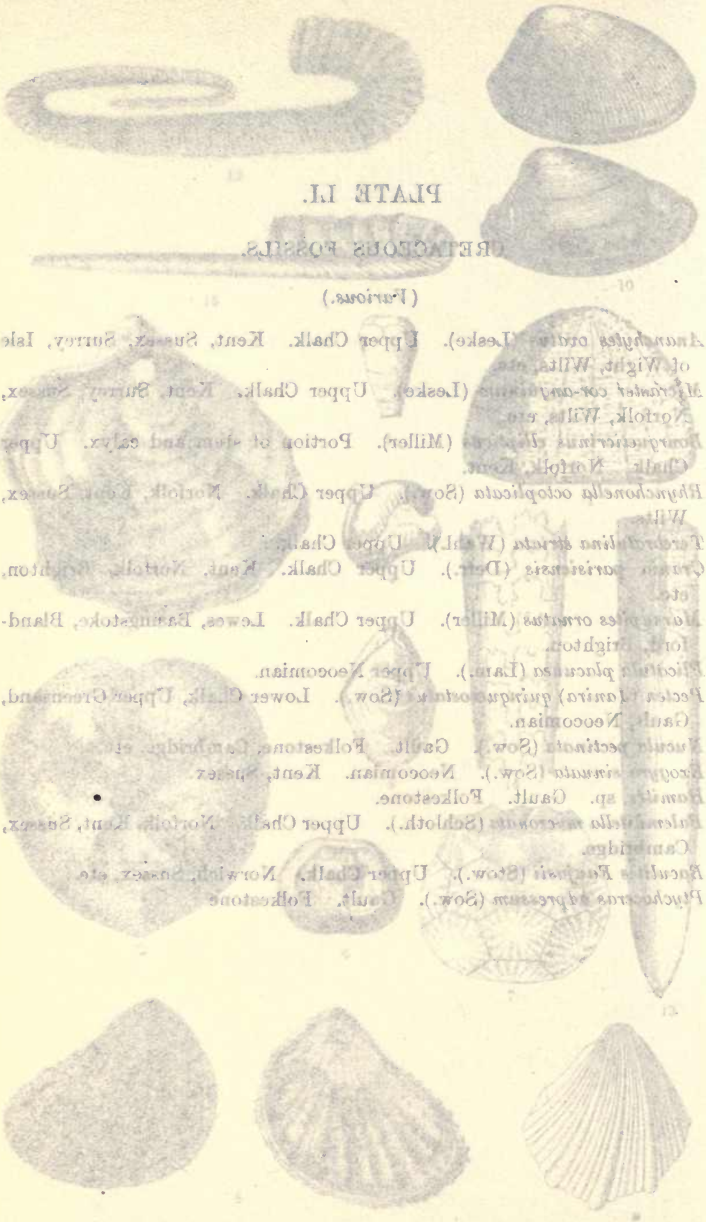
(*Various.*)

PLATE LI.

CRETACEOUS FOSSILS.

(*Various.*)

1. *Ananchytes ovatus* (Leske). Upper Chalk. Kent, Sussex, Surrey, Isle of Wight, Wilts, etc.
2. *Micraster cor-anguinum* (Leske). Upper Chalk. Kent, Surrey, Sussex, Norfolk, Wilts, etc.
3. *Bourgueticrinus ellipticus* (Miller). Portion of stem and calyx. Upper Chalk. Norfolk, Kent.
4. *Rhynchonella octoplicata* (Sow.). Upper Chalk. Norfolk, Kent, Sussex, Wilts.
5. *Terebratulina striata* (Wahl.). Upper Chalk.
6. *Crania parisiensis* (Defr.). Upper Chalk. Kent, Norfolk, Brighton, etc.
7. *Marsupites ornatus* (Miller). Upper Chalk. Lewes, Basingstoke, Blandford, Brighton.
8. *Plicatula placunea* (Lam.). Upper Neocomian.
9. *Pecten* (*Janira*) *quinquecostatus* (Sow.). Lower Chalk, Upper Greensand, Gault, Neocomian.
10. *Nucula pectinata* (Sow.). Gault. Folkestone, Cambridge, etc.
11. *Exogyra sinuata* (Sow.). Neocomian. Kent, Sussex.
12. *Hamites*, sp. Gault. Folkestone.
13. *Balemnitella mucronata* (Schloth.). Upper Chalk. Norfolk, Kent, Sussex, Cambridge.
14. *Baculites Faujasii* (Stow.). Upper Chalk. Norwich, Sussex, etc.
15. *Ptychoceras adpressum* (Sow.). Gault. Folkestone.



CRETACEOUS FOSSILS.

(*Various.*)

to the gar-pike of the North American rivers. Reptilians are abundant and represented by plesiosaurs, deinosaurs, and flying pterodactyls. Among the deinosaurs, the gigantic *Iguanodon* was common.

The local subdivisions of the Wealden are as follow :—

Wealden (Deltaic)	2. Weald Clay		Neocomian.
	1. Hastings Sand	*c.* Tunbridge Wells Sand	
		b. Wadhurst Clay	
		a. Ashdown Sand	

Lower Greensand.—The progressive subsidence of the Neocomian, which affected the whole of North-West Europe, enabled the sea to encroach on the Wealden Delta where the marine sediments of the Lower Greensand were laid down conformably following the Weald Clay.

The stages of the Lower Greensand are as follow :—

Lower Greensand	Folkestone Beds	Mainly Aptian.
	Sandgate Beds	
	Hythe Beds	
	Atherfield Beds	

The rocks of this series consist mainly of grey, yellow, and green sands intercalated with beds of clay, limestone, and ironstone. The green-coloured sands, from which this division derives its name, owe their prevailing green hue to the presence of glauconitic grains.

Some of the calcareous bands, notably those in the Hythe stage, pass into more or less compact limestones, such as that locally called *Kentish Rag*, which is extensively used as a building-stone and for burning into lime.

The Lower Greensand contains a large assemblage of molluscs, among which littoral shells are conspicuous. The most common forms are *Ostrea*, *Exogyra*, *Perna*, and *Arca*, with which are associated many Ammonites and Belemnites.

Among the characteristic species are *Terebratula sella*, *Exogyra sinuata* (Plate L., fig. 1), *Perna mulleti* (Plate L., fig. 2), *Gervillia sublanceolata*, and *Ammonites Deshayesii* (Plate L., fig. 8).

Northern District.

The Lower Cretaceous of Lincolnshire and Yorkshire is wholly marine, and shows a palæontological relationship to the Cretaceous of the Baltic area; and many of the species of molluscs, although unknown in the South of England or in North France, are common in Northern Russia.

The deposits are mainly dark-coloured clays and shales which follow the Jurassic with no appearance of a stratigraphical break. Since they are marine and contain a different fauna, these beds cannot be correlated stage by stage with the deltaic series in the south of England.

The Speeton Clay, which is so well displayed in the neighbourhood of Speeton, north of Flamborough Head in Yorkshire, is the most important division of the northern Lower Cretaceous, and may be regarded as typical of the whole series of which it forms the major part. It contains a prolific molluscous fauna dominated by Belemnites and Ammonites; but in one thin band the characteristic sea-urchin *Echinospatagus cordiformis* is fairly common.

Palæontologically the series has been divided by Lamplugh into four Belemnite zones:—

4. Zone of *Belemnites minimus* (base of Gault).
3. ,, ,, *brunsvicensis*.
2. ,, ,, *jaculum*.
1. ,, ,, *lateralis* (passage-bed).
0. Coprolite Bed.

The Coprolite Bed is a seam of phosphatic nodules about four inches thick, which appears to rest quite conformably on the Upper Kimeridgian with *Belemnites Oweni*. The coprolitic[1] character of the bed might, however, be taken to indicate a short cessation of deposition before the deposition of the marine clays commenced.

Upper Cretaceous.

As a result of the great Cenomanian transgression of the sea the Upper Cretaceous was deposited over a wider and more uniform sea than the Lower Cretaceous; hence it extends far beyond the limits of that division. In some regions the overlap is so great that the Lower and Upper Cretaceous might very well be regarded as two distinct systems.

Lithologically the Upper Cretaceous is divided into three distinct stages, namely an argillaceous stage at the base = the *Gault*; a sandy stage in the middle = the *Upper Greensand*; and a calcareous stage at the top = the *Chalk*.

In England, the Upper Cretaceous is well developed in the Southern, Middle, and Northern Districts; and in each district the various divisions exhibit a remarkable uniformity of character, except the chalk, which in the Northern District is thinner than in the South, and not argillaceous at its base.

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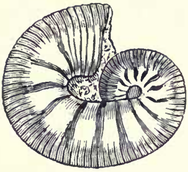
[1] *Kopros* = dung, and *lithos* = a stone..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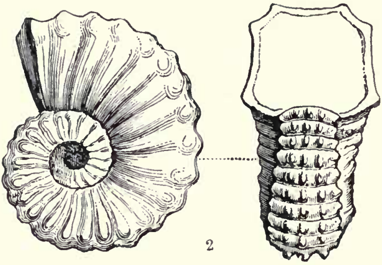
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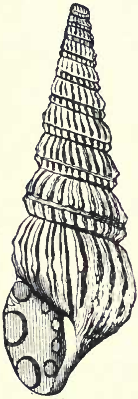
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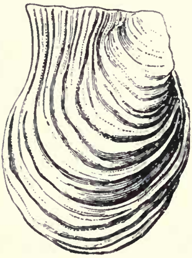
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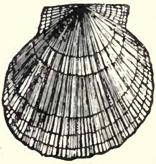
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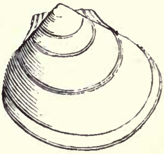
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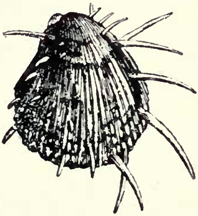
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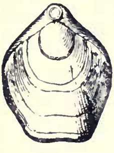
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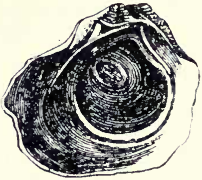
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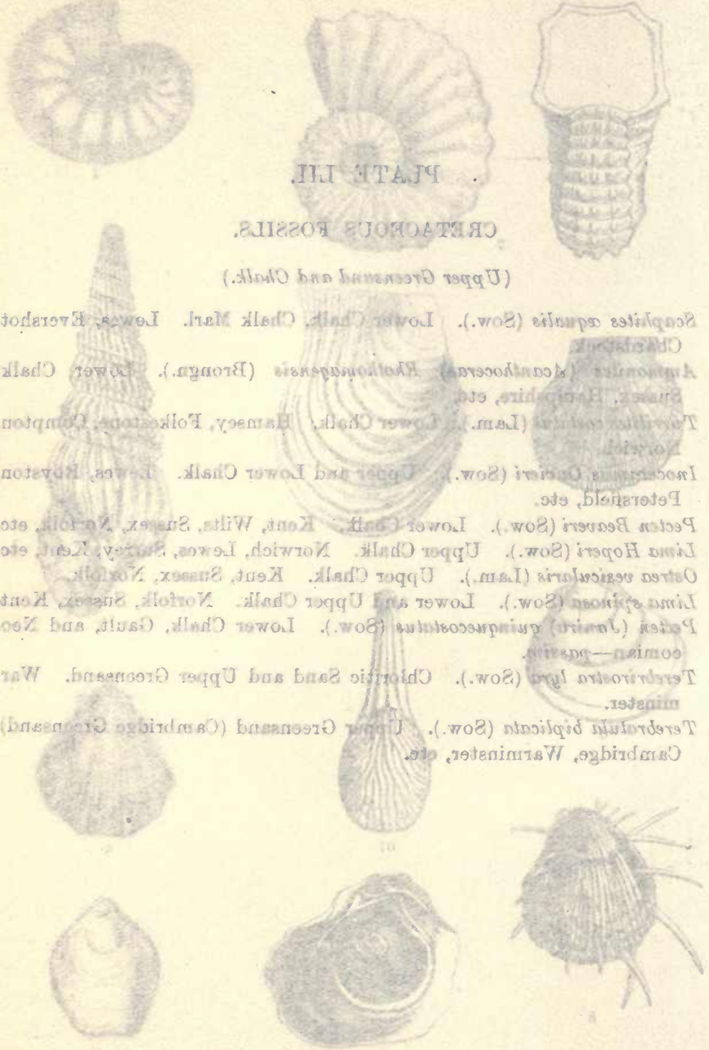
CRETACEOUS FOSSILS.
(*Upper Greensand and Chalk.*)

PLATE LII.

CRETACEOUS FOSSILS.

(Upper Greensand and Chalk.)

1. *Scaphites æqualis* (Sow.). Lower Chalk, Chalk Marl. Lewes, Evershot, Chardstock.
2. *Ammonites* (*Acanthoceras*) *Rhothomagensis* (Brongn.). Lower Chalk. Sussex, Hampshire, etc.
3. *Turrilites costatus* (Lam.). Lower Chalk. Hamsey, Folkestone, Compton, Norwich.
4. *Inoceramus Cuvieri* (Sow.). Upper and Lower Chalk. Lewes, Royston, Petersfield, etc.
5. *Pecten Beaveri* (Sow.). Lower Chalk. Kent, Wilts, Sussex, Norfolk, etc.
6. *Lima Hoperi* (Sow.). Upper Chalk. Norwich, Lewes, Surrey, Kent, etc.
7. *Ostrea vesicularis* (Lam.). Upper Chalk. Kent, Sussex, Norfolk.
8. *Lima spinosa* (Sow.). Lower and Upper Chalk. Norfolk, Sussex, Kent.
9. *Pecten* (*Janira*) *quinquecostatus* (Sow.). Lower Chalk, Gault, and Neocomian—*passim*.
10. *Terebrirostra lyra* (Sow.). Chloritic Sand and Upper Greensand. Warminster.
11. *Terebratula biplicata* (Sow.). Upper Greensand (Cambridge Greensand). Cambridge, Warminster, etc.



CRETACEOUS FOSSILS.

(Upper Greensand and Chalk.)

Upper Cretaceous	3. Chalk	Upper Chalk—Senonian.
		Middle Chalk—Turonian.
		Lower Chalk Cenomanian.
	2. Upper Greensand,	Albian.
	1. Gault, ...	

The Gault.—The Gault is dominated by the argillaceous facies of sediments. Lithologically it consists of stiff, dark blue, marine clay, in places sandy and marly, with lines of pyritic and phosphatic nodules. Its thickness varies from 100 to 300 feet, and in many places it overlaps the Lower Cretaceous.

The Gault contains many beautifully preserved fossils, large numbers of which may be seen at low tide at Copt Point, on the coast near Folkestone, where the Chalk rests directly on the Gault. Ammonites are plentiful, and among other molluscs are *Aporrhais*, *Pleurotoma*, *Cerithium*, *Fusus*, *Natica*, *Dentalium*, *Corbula*, *Pinna*, *Cucullæa*, *Mytilus*, *Ostrea*, *Pecten*, *Inoceramus*, *Cyprina*, and *Pholas*, the last seven being commonest in the higher beds.

A small Belemnite, *Belemnites minimus*, is very abundant and characteristic, as also are *Terebratula biplicata* (Plate LII., fig. 11), *Inoceramus sulcatus*, *I. concentricus*, *Ammonites interruptus*, and *A. rostratus*, all of which are present in the contemporaneous *Red Chalk* of Yorkshire.

Upper Greensand.—This division is dominated by sandy beds, but there is no sharp line of demarcation between it and the Gault. The prevailing colour is dark green, due to the presence of glauconitic grains. In places where the glauconite has become oxidised, the sands assume a yellow, yellowish-brown, or red colour.

Nearly half the molluscs of the Gault pass up into the Upper Greensand, which is now known to be the local equivalent of different horizons of the Chalk series.

Palæontologically the Upper Greensand is divided into two well-marked zones—

2. Zone of *Pecten asper*.
1. „ *Ammonites rostratus*.

The Lower Zone contains, among characteristic species, *Venus submersa*, *Arca glabra*, *Pecten quinquecostatus* (Plate LII., fig. 9), *Ammonites rostratus*, and *Hamites alternatus*; and the Upper Zone, *Terebratula biplicata*, *Pecten asper*, and *Ammonites varians*.

In the Central District the Gault and Upper Greensand (Albian) possess the same physical characteristics and fossils as in the south of England, but going northward the sandy beds comprising the

Upper Greensand are gradually replaced by clay, and in Bedfordshire finally disappear, so that north of this the Upper Greensand is no longer recognisable as a separate member of the Upper Cretaceous.

In the Northern District the Albian (Gault + Upper Greensand), now mainly represented by clay, thins out and gradually passes into a bed of red chalk which is well seen in the sea-cliffs of Hunstanton in Norfolk, where it is about three feet thick and contains the characteristic fossils of the Albian of the south of England.

Going northwards, the *Red Chalk* expands to ten or twelve feet, and in the neighbourhood of Speeton still further thickens and passes into beds of reddish-coloured marls and clays with irregular seams of red chalky marl.

The Chalk.—The Chalk is the most conspicuous of the Upper Mesozoic formations of North-West Europe. It is a soft earthy limestone mainly composed of the shells of foraminifera among which the genus *Globigerina* predominates. At its base it becomes argillaceous, forming what is called *Chalk Marl*; and in some places it contains grains of glauconite.

Nodules of flint arranged in lines parallel to the original planes of deposition are scattered throughout the Chalk and are particularly prevalent in the *Upper Chalk*, which has for that reason been called *White Chalk with flints.* The *Lower Chalk* has been called the *White Chalk without flints*; but this basis of subdivision is not satisfactory, since the lower part of the Chalk frequently contains flints, and the upper part in some cases does not.

The Chalk Series is divided, on palæontological grounds, into three distinct stages, namely :—

$$\text{Chalk Series}\begin{cases}\text{Upper Chalk —Senonian.}\\\text{Middle Chalk—Turonian.}\\\text{Lower Chalk—Cenomanian.}\end{cases}$$

Conditions of Deposition.—The Chalk is mainly composed of foraminiferal ooze, a kind of deposit which at the present day is always associated with deep oceanic waters. The geographical position of the Chalk of North-West Europe and North America, and the presence in it of sandy beds as well as a mixed molluscous fauna, including *Terebratulina*, *Rhynchonella*, *Pecten*, *Ammonites*, *Belemnitella*, and other genera, besides numerous sea-urchins and the crinoid *Marsupites*, would seem to indicate that the original calcareous sediments were laid down in clear but comparatively shallow waters such as now exist in the fiords of Norway and New Zealand.

The palæontological zones into which the Upper Cretaceous is divided are as follow :—

Upper Chalk	Zone of *Ostrea lunata*	Senonian.
	,, *Belemnitella mucronata*	
	,, *Actinocamax quadratus*	
	,, *Marsupites testudinarius*	
	,, *Micraster cor-anguinum*	
	,, ,, *cor-testudinarium*	
	,, *Holaster planus*	
Middle Chalk	,, *Terebratulina lata*	Turonian.
	,, *Rhynchonella Cuvieri*	
Lower Chalk	,, *Holaster subglobosus*	Cenomanian.
	,, *Ammonites varians*	
Upper Greensand and Gault	,, *Pecten asper*	Albian.
	,, *Ammonites rostratus*	
	,, ,, *lautus*	
	,, ,, *interruptus*	
	,, ,, *mammillatus*	

Climate.—The character of the land vegetation, reptilians, and marine mollusca would seem to indicate the prevalence of a semi-tropical to tropical climate and warm seas such as may now be found on the coasts of West Africa and Malaysia.

Scotland.

Cretaceous rocks occur in the Isle of Mull and on the margin of the neighbouring Morvern Peninsula. In these areas they owe their preservation to the covering of Tertiary basalts. The rocks belong to the Upper Cretaceous, and contain evidence of deposition on the shores of an estuary, or landlocked inlet of the sea.

Ireland.

Upper Cretaceous rocks appear round the borders of the Antrim plateau, and, as in West Scotland, owe their preservation to the covering plateau of basalts. They rest unconformably on Jurassic and older rocks, and bear witness to the wide-spread character of the great Cenomanian transgression.

Cretaceous of other Countries.

North France and Belgium.—The Cretaceous rocks of North France and Belgium are lithologically and palæontologically closely related to the Cretaceous of England of which they are obviously the eastern extension laid down in a prolongation of the same sea.

The subdivisions recognised in this region are :—

- Upper Cretaceous
  - 8. Danian.
  - 7. Senonian.
  - 6. Turonian.
  - 5. Cenomanian.
- Lower Cretaceous
  - 4. Albian.
  - 3. Aptian.
  - 2. Urgonian.
  - 1. Neocomian.

The characteristic fossils of the corresponding English subdivisions are well represented in these stages.

Danian.—The Danian stage, so called from its typical development in East Denmark, seems to bridge the hiatus between the Senonian and the Landenian (or lowermost Eocene) as developed in England. It comprises both marine and freshwater sediments; and its fauna, while mainly Cretaceous, contains many Cainozoic types.

Rocks of Danian age are well developed in the northern Cretaceous basin of Western Europe, where they consist chiefly of grey and yellowish-coloured chalk and chalky marls that usually rest on an eroded surface of the underlying Senonian chalk.

The so-called Pisolitic Limestone of French geologists occurs in isolated patches in the neighbourhood of Paris, and in the department of Oise and Marne, and rests unconformably in different parts of the Cretaceous series, forming *passage-beds* into the Tertiary formations. The lowermost of these deposits is a hard, coarse-grained limestone containing the characteristic species *Neithea quadricostata* and *Nautilus hebertinus*. The concretionary limestone of the upper division, representing the *Montian* sub-stage of the Cretaceous system, has yielded among many fossil molluscs, *Pleurotoma penultima*, *Neithea quadricostata*, *Lima tacta*, and the very characteristic Danian cephalopod, *Nautilus danicus*.

At Mons, in South Belgium, the calcareous beds of Danian age underlying the town have been proved by boring to be 300 feet thick. The *Mons Chalk* is mainly composed of Cretaceous foraminifera and calcareous algæ, and with these are associated many Tertiary genera, including *Triton*, *Fusus*, as well as a few freshwater forms, such as *Pupa*, *Physa*, and *Bithinia*.

The *Maestricht Chalk* in Holland contains a rich fauna, which includes *Nautilus danicus*, *Baculites Faujasi*, *Belemnitella mucronata*, *Ostrea vesicularis*, *Cidaris Faujasi*, *Micraster tercensis*, some hippurites, many fish remains, and numerous bones of *Mosasaurus camperi*, the last of the great Cretaceous mosasaurids.

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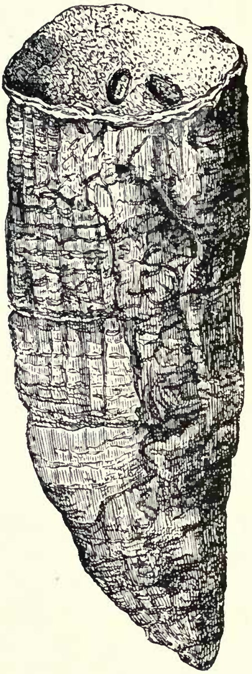

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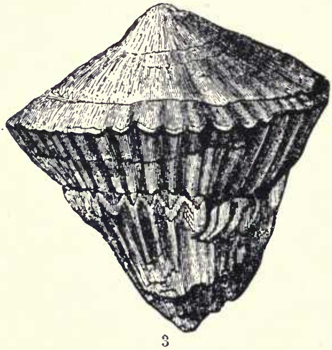

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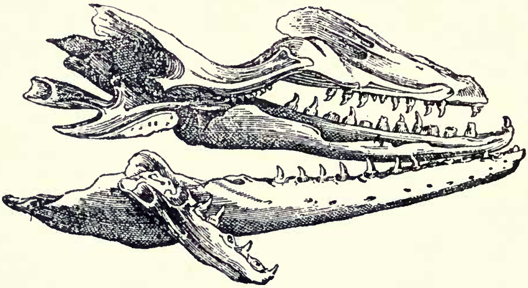


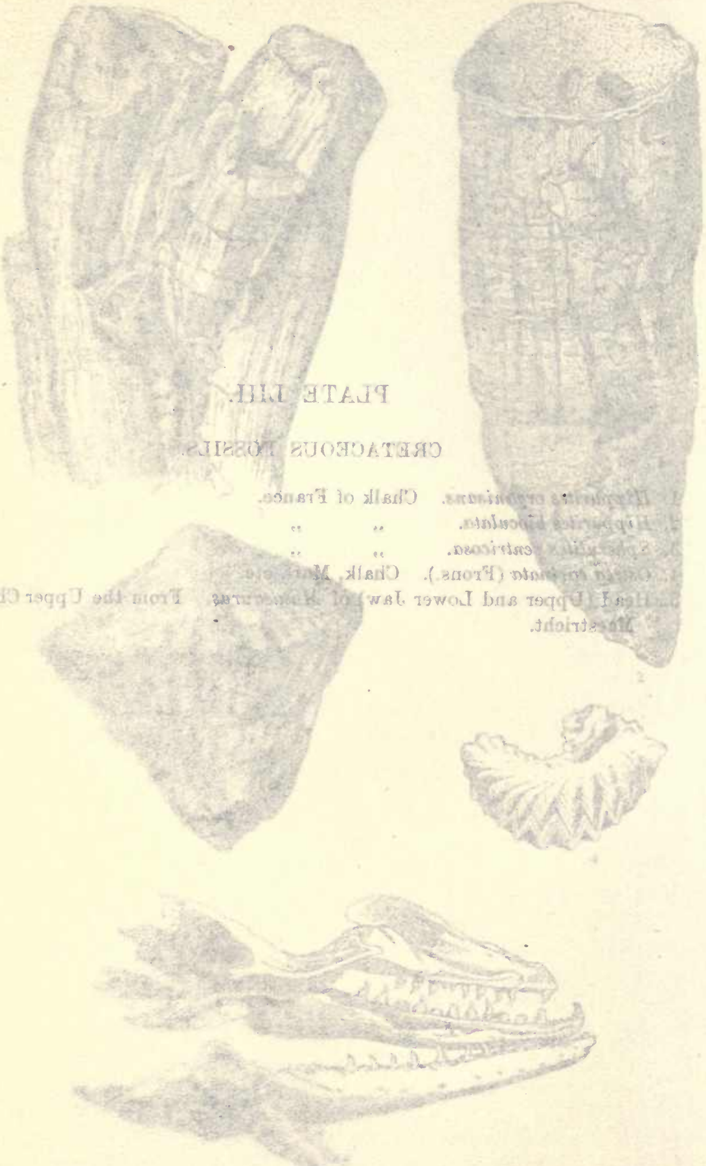
5

CRETACEOUS FOSSILS.
(*Chalk.*)

PLATE LIII.

CRETACEOUS FOSSILS.

1. *Hippurites organisans.* Chalk of France.
2. *Hippurites bioculata.* ,, ,,
3. *Spherulites ventricosa.* ,, ,,
4. *Ostrea carinata* (Frons.). Chalk, Marl, etc.
5. Head (Upper and Lower Jaw) of *Mosasaurus.* From the Upper Chalk of Maestricht.



CRETACEOUS FOSSILS.

(CHALK.)

The *Faxoe Chalk*, which forms the lower division of the Danian in East Denmark, is a hard yellow limestone full of bryozoa, with *Nautilus danicus* and numerous echinoderms, the latter including the genera *Holaster*, *Tremnocidaris*, and *Dorocidaris*. The *Saltholm*, or upper division, which is a chalk with flints, has been proved by boring to occupy a wide tract around Copenhagen under the glacial drift. It contains an abundant fauna in which *Nautilus danicus*, *Baculites Faujasi*, *Belemnitella mucronata*, *Ostrea vesicularis*, and *Terebratula carnea* are conspicuous. Similar strata and fossils occur in the south of Sweden.

The Danian is also strongly developed in the south of France, where it is represented by marly, chloritic, and compact limestones over 600 feet thick, with an abundant fauna, which includes such distinctive forms as *Nautilus danicus* and *Micraster tercensis*.

The presence of *Hippurites* and large echinoderms in the Danian of Denmark and Sweden indicates the prevalence of a comparatively warm climate in the Baltic zone just prior to the advent of the Eocene.

The Danian stage appears to have no representative in England, unless the uppermost Cretaceous beds which appear on the Norfolk coast, at Trimmingham, near Cromer, are the equivalents of the lowest Danian of the continental area.

A very complete succession of Cretaceous strata occurs in Persia, India, Japan, and United States, including representatives of the Senonian and lower Danian.

The highest division of the Upper Cretaceous on the east coast of Southern India, from Pondicherri to Trichinopoli, contains the well-known Danian fossil *Nautilus danicus*, which has also been identified in the Upper Cretaceous of Persia.

The great freshwater Laramie formation, which forms the chief Lignitic series of North Utah and Wyoming, reaches from the Senonian to the Danian, and is separated by a strong unconformity from the lowermost Eocene. It is believed by some writers to form a *passage-bed* leading up to the Tertiary formations.

No strata of Danian age have been recognised in Australia or New Zealand. Wherever Cretaceous and Eocene formations are present in these regions, the palæontological break is always sharply defined, even in places where the stratigraphical discordance is absurdly insignificant.

It should be noted that *Ammonites*, *Belemnites*, and *Turrilites* disappear before the Danian stage is reached.

Germany.—The Cretaceous rocks of Germany and the Baltic area were laid down in prolongations of the same sea as the English Cretaceous of the Northern District, and consequently present the same palæontological succession, and to some extent the same lithological features.

In Germany, the Cretaceous System is well developed in Bohemia, Saxony, Hanover, and Westphalia. The soft chalk of North France when traced eastward into Westphalia passes into sands, soft sandstones, and marly beds, which expand to an enormous thickness in the gorge of the Elbe.

The Upper Cretaceous terrestrial beds of Aix-la-Chapelle contain an abundant flora, comprising many monocotyledons and dicotyledons, some of which show a curious resemblance to forms found in the Upper Cretaceous beds of Northern Greenland.

Russia.—Cretaceous rocks cover an extensive tract in the valleys of the Dneister, Don, and Volga, and generally bear a relationship to the Cretaceous of North-West Europe.

Mediterranean Basin.—There is a great development of the southern facies of the Cretaceous in the regions abutting on the Mediterranean Basin, notably in Portugal, Spain, South France, Sicily, Italy, Switzerland, the Carpathians, Greece, and Asia Minor. Also in Morocco, Algiers, Tunis, and Egypt they cover a vast area which extends almost to the southern limits of the Sahara Desert.

Palæontologically, the Mediterranean facies is characterised by the extraordinary prevalence of the peculiar Lamellibranch *Hippurites*, which is a cone-shaped shell provided with a lid. The *Hippurites* lived in banks in shallow water, and grew in such numbers as to compose thick beds of limestone. Ammonites attain a large size and belong to the sub-genera with free-whorled, hooked, and highly ornamented shells. Among these, *Buchiceras* is widely spread and characteristic.

A remarkable and interesting feature of the Cretaceous as developed in the Alps is a vast pile of sandstones and shales commonly known to Continental geologists as the *Flysch* or *Vienna Sandstone.* This rock formation extends from south-west Switzerland through the northern Alps to Vienna. It is conspicuously unfossiliferous, with perhaps the exception of some fucoid-like markings which afford no evidence of its age. The lower portions of this great accumulation of fluviatile deposits are known to be Cretaceous from the presence of fragments of *Inoceramus* and intercalated beds of limestone which contains Neocomian fossils. The upper portion may be Eocene or even later date, but this is not certain.

The lithological character of this mass of unfossiliferous rocks is so distinctive that the name *Flysch* is now recognised as a descriptive term for all such accumulations of similar unfossiliferous strata, regardless of their age.

India.—The Cretaceous System is represented in India by a great assemblage of marine and fluviatile deposits occurring both in the Peninsular area and the Himalayan. The rocks are largely limestones and shales, but sandstones and shales of the Flysch facies are extensively developed in both regions.

The Hippurite limestones which are characteristic of the Mediterranean facies of Southern Europe stretch into Asia Minor and Persia, whence they pass into Baluchistan, Northern Himalayas, Tibet, Upper Burma, and China.

All the stages of the Cretaceous have been recognised in the coastal region by their faunas, which show a remarkable relationship to those of North-West Europe.

Upper Cretaceous	Danian, with *Nautilus danicus.* Senonian. Turonian. Cenomanian. Not known in Himalayan region.
	Albian. Absent in Himalayan region.
Lower Cretaceous	Aptian. Neocomian.

The effects of the Cenomanian transgression are particularly evident in the Peninsular region, where the Upper Cretaceous covers large tracts that in many places extend inland far beyond the limits of the Lower Cretaceous.

A notable feature of the Upper Cretaceous of India is the evidence of volcanic outbursts on a titanic scale and, so far as is known, unparalleled in the history of the globe. Towards the close of this period a succession of floods of lavas overwhelmed the greater portion of the Peninsular area, in places attaining a depth of 10,000 feet. The lavas are mainly augite basalts and dolerites that constitute what is commonly known as the *Deccan Trap.*

Concurrent with these outbursts, violent volcanic eruptions also took place in the Himalayan area, the ejected material consisting mainly of tuffs supposed to be submarine, rhyolitic, andesitic, and basaltic lavas, all of which are intruded by later gabbros and chrome-bearing serpentines.

North America.—The Cretaceous rocks of North America fall into two great formations that differ greatly in lithological character, fauna, and geographical distribution, this last arising from the Cenomanian transgression, the effects of which are perhaps more marked in North America than in any other continent.

In North America there is the same faunal contrast between the north and south facies as in Europe. In Mexico, Texas, and California, the southern or equatorial facies is characterised by the presence of *Hippurites*, *Nerinæa*, and the Ammonite *Buchiceras*, all found in Southern Europe, as also in Syria, Persia, and India.

The northern facies with white chalk is typically developed in Colorado.

The Lower Cretaceous, or *Comanchean System*, as it is sometimes called by American geologists, extends as a narrow strip along the old Atlantic border from New Jersey southward to South Carolina, and through Virginia, Georgia, Alabama, and Tennessee. From the Mississippi Basin it sweeps round the Mexican Gulf, whence it passes northward to Texas and southward to Mexico. It is also typically developed on the Pacific side of the continent, notably in the Sacramento Valley and coastal ranges of California, Oregon, and Washington.

The Upper Cretaceous follows the Lower Cretaceous round the old Atlantic border and Mexican fringe, whence it spreads out over Texas. Here it overlaps the Lower Cretaceous and extends northward as a broad belt through the Western Interior Basin to British Columbia and Alaska.

In this region the Cenomanian transgression amounted to over two thousand miles, and curiously enough it followed a line of depression running parallel with the axis or fulcrum along which the tilting of the continent took place in the Middle Mesozoic.

The Lower Cretaceous Series consists mainly of sandy, clayey, and calcareous deposits of marine origin ; and the Upper Cretaceous mainly of estuarine, lacustrine, and terrestrial sediments.

Lower Cretaceous.—On the Atlantic border, this great group of beds is known as the *Potomac Series*, and in the Mexican Gulf region as the *Tuscaloosa Series*. These two series are in part, or perhaps mainly, contemporaneous.

The Potomas Series is chiefly composed of estuarine and terrestrial deposits, and the Tuscaloosa Series of marine sediments, among which chalk and compact limestones are well represented.

In Mexico the Lower Cretaceous attains a vast thickness, which is variously estimated at from 10,000 to 20,000 feet ; and in California the Shastan Series (=the Comanchean) has an estimated maximum thickness of 26,000 feet.

Upper Cretaceous.—The subdivisions of this series in the Interior Basin, where we have its greatest development, are as follow :—

Upper Cretaceous
4. Laramie.—Mainly brackish waters, lacustrine and terrestrial, with seams of lignite.
3. Montana.—Lower division, marine ; upper, estuarine.
2. Colorado.—Lower portion mostly shales ; upper portion, chalk.
1. Dakota.—Mainly continental and estuarine, with coal-seams.

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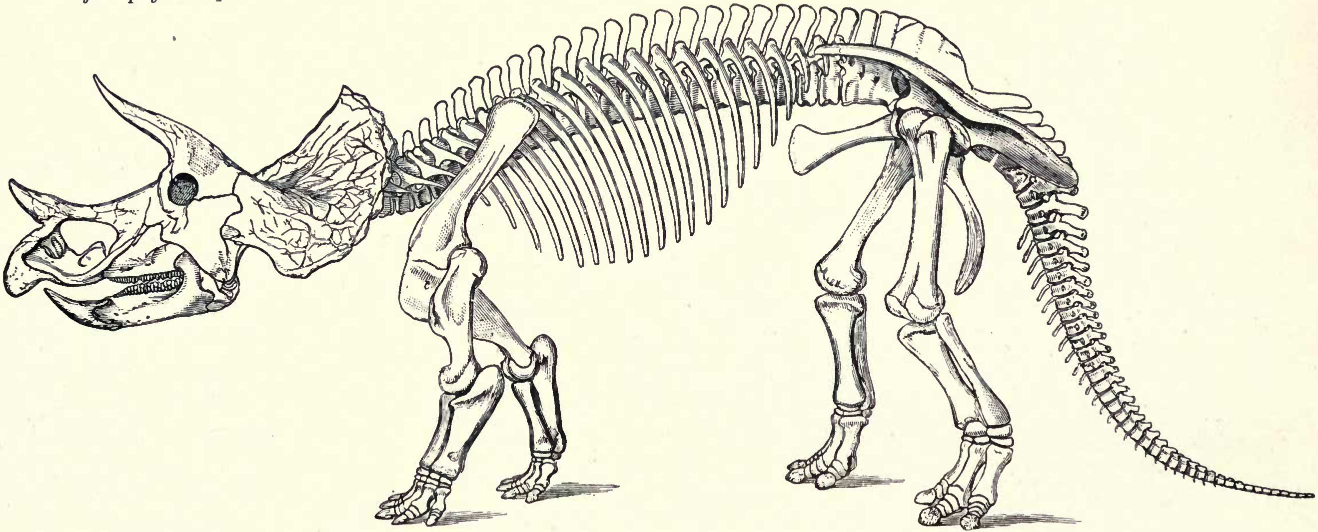
[PLATE LIV.



RESTORATION OF TRICERATOPS PRORSUS. CRETACEOUS, WYOMING. (Marsh, U.S. Geol. Survey.)

The Upper Cretaceous rocks at one time stretched in a continuous sheet from the Gulf of Mexico to Alaska, and were laid down in an inland basin on the shores of which coal vegetation grew luxuriantly. The sea had free access to the basin until the middle of the Montana stage, when a general uplift introduced brackish-water conditions, and eventually cut off all communication with the sea. It was in this great land-locked basin that the famous Laramie lignitic formation was laid down. This inland basin was 2000 miles long and 500 miles wide.

The Laramie Series follows the Montana Series conformably, and is overlain unconformably by the Eocene. It is the principal coal-bearing formation of the Western States, altogether covering an area of about 100,000 square miles. The coal belongs to the lignitic variety, except in some parts of Colorado, where it has been altered to anthracite by local igneous intrusions.

At the close of the Cretaceous there was a sudden and violent revival of volcanic activity in many parts of North America; and the outbursts were particularly intense in the Crazy Mountain area of Montana.

Fauna and Flora.—The Cretaceous Systems of North America contain prolific and varied faunas and floras, among which the northern and southern facies of Europe are typically developed.

The reptilian fauna is specially notable for the number and variety of its deinosaurs, pterodactyls, crocodiles, turtles, and plesiosaurs.

The marine molluscous fauna is mainly dominated by Ammonites and Belemnites, many of which, as in Europe and Asia, possess a zonal importance. All the characteristic genera of Lamellibranchs, Gasteropods, and Sea-urchins that distinguish the European Cretaceous are well represented in North America.

The land flora of the Laramie Lignitic Series contains a large assemblage of forest trees, including representatives of the oak, willow, beech, plane, poplar, maple, hickory, fig, and sassafras, with many ferns, cycads, and conifers.

South America.—Cretaceous rocks are widely distributed throughout Brazil, Peru, Chile, and Patagonia.

In Brazil the Upper Cretaceous division extends far beyond the domain of the Lower Cretaceous, and consists mainly of marine sediments. Rocks of Senonian age rise into the summit of the Eastern Andes, and in some parts of the chain appear at a height of over 14,000 feet above the sea.

The presence of extensive sheets of intercalated lavas and tuffs shows that the close of the Cretaceous in this continent was a time of intense volcanic activity.

North Africa.—The Lower Cretaceous rocks of North Africa are mostly confined to the region fringing the south-west borders of the Mediterranean basin, including the Atlas Mountains. But as a result of the Cenomanian transgression, the Upper Cretaceous Sea overspread all the low-lying areas of North Africa, thereby covering the greater portion of what are now the Saharan, Libyan, and Nubian deserts. Altogether the sea invaded an area amounting to many hundred thousand square miles.

The best-known and perhaps most widespread member of the Upper Cretaceous in North-East Africa is the *Nubian Sandstone*, a reddish-brown or grey sandstone which contains only silicified wood and in many places bears a curious resemblance to the *Desert Sandstone* of Queensland. In the Libyan Desert the Nubian Sandstone is overlain by white chalk which, among other fossils, contains the sea-urchin *Ananchytes ovata*, a characteristic form of the Senonian of North-West Germany.

From Egypt the Nubian Sandstone passes into Syria and Arabia, where Upper Cretaceous rocks with *Hippurites* are very largely developed, and include the famous fish-bearing Senonian rocks in Lebanon.

South Africa.—The Cretaceous rocks of South Africa are divided into two groups, which occupy separate geographical areas. Both are shallow-water marine deposits, and each group begins with a coarse basal conglomerate.

The two groups are the *Uitenhage Series* and the *Pondoland Series*. The latter occupies two narrow strips along the coast; while the former is mainly displayed in a disturbed and folded zone lying between the Karoo and the coast.

The Uitenhage Series consists mainly of sandstones, clays, shales, and limestones, with conglomerates at the base. It is divided into three stages:—

Lower Cretaceous	3. Sunday's River Beds	Mainly Neocomian.
	2. Wood Beds	
	1. Enon Beds	

The clays of the *Enon Beds* have yielded the remains of deinosaurs; and the Wood Beds contain an interesting series of fossil plants comprising many ferns, cycads, and conifers. Among the ferns are such well-known genera as *Tæniopteris*, *Sphenopteris*, and *Cladophlebis*. Some of the beds are crowded with the broad fronds of the cycad *Zamites*, of which four species have been identified, including *Z. recta* and *Z. africana*. The conifers are represented by *Araucarites*, *Taxites*, *Conites*, and others.

Intercalated with the *Wood Beds*, there are two or more bands of marine deposits in which the molluscs *Ostrea*, *Psammobia*, *Pecten*, and *Turbo* have been found. In the fossil wood found in this formation there have also been discovered many examples of the small boring mollusc *Actæonina atherstonei.*

The *Sunday's River Beds* are shallow-water or estuarine, and contain a rich molluscous fauna which consists mainly of Lamellibranchs, Gasteropods, and Cephalopods. The Lamellibranchs include such littoral shells as *Astarte, Avicula, Cardita, Cucullæa, Exogyra, Gervillia, Lima, Pecten, Perna, Pinna, Mytilus, Modiola,* and *Trigonia*; the Gasteropods, *Natica, Patella, Trochus,* and *Turbo*; and the Cephalopods, *Baculites, Crioceras, Hamites,* and *Belemnites.*

The Pondoland Series occurs in two strips, the Umzamba and the Embotyi. The Umzamba, which is the more important, lies on the coast near the Natal boundary. It consists mainly of alternating bands of shelly limestone and hard marly clays of marine origin, with a large number of fossil molluscs, including Cephalopods, which show a singular relationship to those of the Upper Senonian of Northern India, Japan, Vancouver Island, and Chile.

Australasia.—Cretaceous rocks occupy an enormous area in the Northern Territory, Queensland, and Western New South Wales. They are divided into two series, namely:—

Upper Cretaceous (2)—Desert Sandstone.
Lower Cretaceous (1)—Rolling Downs Series.

The *Rolling Downs Series* consists mainly of marine clays which follow the Jurassic rocks quite conformably. It is mainly developed in Queensland, where it occupies or underlies an area of 500,000 square miles. The clays of this widespread formation constitute an impervious covering, and thereby imprison the fresh water contained in the underlying sandstones. The water rises freely to the surface when tapped by bore-holes. The economic importance of the Rolling Downs formation to the dry interior of Queensland is almost incalculable.

The *Desert Sandstone* consists of rusty-brown, gritty sandstones which are frequently current-bedded. It mostly occurs as isolated patches and outliers which form hills, ranges, and plateaux scattered throughout Queensland and Western New South Wales. Its present distribution shows conclusively that it was at one time a continuous sheet which occupied an area exceeding 500,000 square miles. This great formation is quite undisturbed, and rests unconformably on the Lower Cretaceous and on older rocks. We now have evidence that the perplexing Cenomanian transgression of the sea was world-wide and probably contemporaneous in both hemispheres.

The Desert Sandstone was laid down partly in a shallow sea bordering a great continent, and partly on the neighbouring low-lying desert lands. Near the bottom of the series on the present coast-line it contains intercalated marine beds from which a few molluscs have been obtained, including *Rhynchonella croydonensis*, *Leda elongata*, *Avicula alata*, and casts of Belemnites. The same beds contain the sea-urchin *Micraster sweeti*. In the Desert Sandstone in Western New South Wales there have been found the remains of the reptilian *Cimoliosaurus*; and in Central Queensland, broken plants and silicified trees in abundance. At Cooktown it contains coal-seams and silicified trees.

The surface of the Desert Sandstone is frequently covered with a thin enamel or glaze of silica deposited by water. The siliceous cement stones of South New Zealand, and the surfaces of the mushroom-shaped deposits of siliceous sinter in the Hauraki Peninsula in North New Zealand, are also covered with the same glaze, which is only formed on weathered surfaces.

On the Darling River the Desert Sandstone contains deposits of opal.

In New Zealand the Cretaceous *Waipara Series* consists of basal conglomerates and sandy beds with seams of coal and shales which contain the leaves of dicotyledonous plants. The Coal-Measures are followed by marly or shaly clays with lines of calcareous concretions that frequently contain saurian remains. Then follow glauconitic greensands which are conformably overlain by chalky and hard limestones which close the succession. Passing northward from Waipara, the chalky limestone (*Amuri Limestone*) expands and replaces the hard limestone (*Weka Pass Stone*), and is called the *Grey Marl*.

The reptilian remains found in the marly clays below the greensands include representatives of *Plesiosaurus*, *Mauiosaurus*, *Polycotylus*, and others. In the same beds there are found the teeth of *Lamna* and *Hybodus*, and the molluscs *Trigonia*, *Conchothyra parasitica*, which is a characteristic Cretaceous form, *Rostellaria* and *Belemnites*.

The Waipara Series is marginal to the present coasts, but in a few places it creeps into land-locked mountain basins to which the sea had free access.

Landscape and Physical Features.—The Cretaceous System, as seen in different lands, presents a great diversity of surface forms. The effects of denudation are found to vary with the character and succession of the rocks, the amount of tilting and faulting they have suffered, the height above the sea, the amount of rainfall, and general climatic conditions. Even the same rock-formation may assume different landscape forms in different regions.

The Chalk, in England, owing to its superior resisting power to the effects of subaerial denudation, wherever it occurs, forms striking features in the landscape. Thus the ranges of hills known as the North and South Downs, the Salisbury Plain, Chilterns, Lincolnshire Wolds, and Yorkshire Wolds, all owe their origin to the wearing away of the softer clays and sands and the survival of the chalk notwithstanding the wasting influence of the weather. In the same way the white cliffs of Dover, in South-East England, and of Flamborough Head on the north-east coast, owe their striking appearance to the resistance the chalk has offered to the assaults of the sea. Moreover, in the Isle of Wight, where the Cretaceous rocks are tilted at high angles, the chalk forms the central ridge which traverses the island, the surrounding softer rocks having been worn away by denudation.

In arid regions the effects of subaerial denudation are always strikingly uniform, and there is seldom seen the diversity of surface features which characterises temperate climates with an abundant rainfall. In temperate regions the rock-formations become dissected into a complex of ridges and valleys, but in arid regions the general effect of the varying temperature and wind is to reduce the whole landscape to a monotonous level surface.

The Nubian Sandstone of North Africa forms long lines of even escarpment in the Libyan Desert; and the Desert Sandstone of North-East Australia frequently assumes the form of isolated flat-topped ridges bounded by steep walls, like the *mesas*[1] of Colorado; or pyramidal hills barred with the horizontal parallel lines of stratification, like the *buttes* of Wyoming.

Economic Minerals.—The Cretaceous System is notable for its valuable deposits of lignitic coal as found in the Laramie formation of the Western Interior States of North America; and in the Waipara Series of New Zealand. The chalk and other limestones of this system are also of great economic importance, in England, France, and elsewhere, as a source of lime for the manufacture of cement, and for agricultural purposes.

SUMMARY.

(1) The Mesozoic era is divided into three great systems, the *Triassic*, *Jurassic*, and *Cretaceous*. Generally speaking, the Triassic is the connecting-link with the Palæozoic era, and the Cretaceous with the Cainozoic.

(2) The Triassic as developed in England is continental, and shows a continuation of the conditions that prevailed in the Permian; but in Continental Europe there are two distinct facies of deposits, each occupying different geographical areas, and each characterised by a distinctive fauna. The two facies

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[1] Sp. *Mesa* = a table.

are the *Continental* and the *Marine,* the former typically developed in Central Germany and hence called the *German* facies ; and the latter in the Alps, and hence known as the *Alpine* facies.

The deposits of the continental facies were laid down in inland basins or Mediterranean seas that after a time were cut off from all access to the sea. The extensive and valuable beds of rock-salt and gypsum associated with these deposits show that the climatic conditions of Central Europe and the corresponding latitudes in North America were not unlike those now prevailing in the arid regions of North Africa and Central Australia.

The Triassic deposits of the Alpine facies are marine, but the fauna is that of shallow water.

The Triassic System is specially distinguished by the appearance in it of the earliest known mammals which belong to a primitive type apparently related to the existing marsupials of Australia.

(3) The deposits and fossils of the Jurassic System show that the continents of that period were clothed with a rank vegetation, while the estuaries and seas swarmed with molluscs, fishes, and huge reptiles. Moreover, the forests teemed with insects, and the sea-shore was frequented by the peculiar toothed *Archæopteryx*, the earliest known bird.

The faunas of the Jurassic may be divided into geographical zones which encircle the globe in a direction parallel to the equator, and correspond to the biological zones that now exist in each hemisphere. This is the first evidence of the existence of climatic zones on the globe.

Ammonites were very numerous in the Jurassic seas ; and the different species were so widely distributed throughout the globe and so limited in vertical range, that they are now useful in subdividing the various stages of the system into palæontological zones.

Cycads were so abundant and prominent among the land vegetation, and reptiles so numerous on the land, in the air, in the deltas and seas, that the Jurassic has been sometimes called the *Age of Cycads*, and sometimes the *Age of Reptiles.*

(4) The Cretaceous System everywhere falls into two great divisions, the Lower Cretaceous and the Upper Cretaceous. These two divisions are frequently associated in the same regions ; but in all the continents, in both hemispheres, the Upper Cretaceous passes on to older rocks and stretches far beyond the limits of the Lower Cretaceous. This remarkable distribution of the Upper Cretaceous rocks was due to a relatively sudden invasion or transgression of the sea all over the globe, whereby all the low-lying lands and valleys fringing the continents were overwhelmed by the sea. The cause of this great inundation is unknown, but it

may have been connected with the collapse of the Gondwana-Land continent, which we know existed in the Indian Ocean area up till the close of the Jurassic and well into the Cretaceous period.

The marine life of the Cretaceous was even more abundant than that of the Jurassic; and while its general facies is distinctively Mesozoic, it is characterised by the appearance of many genera of marine molluscs which still live in our seas.

The Cretaceous flora is specially notable for the advent of angiosperms or flowering plants, including monocotyledons and dicotyledons, among which were representatives of most of the forest trees of the present day. Ferns, cycads, and conifers now grew side by side with the oak, beech, plane, willow, and other familiar trees; hence the general aspect of the forests must have resembled that of the existing forests of the warm temperate zones of the present day.

The Jurassic reptiles were still present in all parts of the globe, and particularly numerous in North America; but they disappeared before the close of the Cretaceous period, as also did the voracious Ammonites and Belemnites. The *Nautilus*, the most ancient of the Cephalopods, survived the Cretaceous and still lives in warm tropical seas. Its persistence is possibly due to its habitat lying in the open deep seas, where it would be less affected by continental changes than the shallow-water Ammonites and Belemnites.

Two distinct types of marine fauna are present in Europe and America, the northern and southern, the former or Central European characterised by soft foraminiferal chalk, and the latter or Equatorial by hard limestones frequently composed of the shells of the curious *Hippurites*, which also spread eastward as far as Northern India and Tibet, and westward to Jamaica, Texas, and California, but appear to be unknown in the Southern Hemisphere.

CHAPTER XXXI.

CAINOZOIC OR TERTIARY ERA.

Eocene and Oligocene Systems.

THE Cainozoic is the youngest of the four grand divisions into which geological time is divided, and embraces the period from the end of the Cretaceous to the present time.

The palæontological break between the Lower Tertiary and the Chalk is the most striking and universal in the geological history of the globe. But the stratigraphical break is not, as might reasonably be expected, correspondingly great. On the contrary, it is seldom conspicuous, and in many places is scarcely visible, which renders the sudden change in the organic life of the Earth all the more remarkable and puzzling.

Great changes took place in the relative distribution of land and sea during the interval bridging the Chalk and Eocene; and there is abundant evidence that they were mainly due to a worldwide recession of the sea. But these changes were inconsiderable compared with those caused by the great Cenomanian transgression, which, as we know, was followed by no conspicuous acceleration in organic development. Nevertheless, we are probably not far from the truth when we assume that the remarkably sudden disappearance of old forms, and the advent of many new inhabitants of the globe in the interval between the Chalk and Lower Tertiary period, were mainly due to physical and climatic changes; and although the stratigraphical break is apparently small, the time occupied in these changes must have covered a vast period of time.

Fauna and Flora.—The life of the Tertiary era is distinguished from the Cretaceous by the disappearance of many well-established Mesozoic genera and the sudden appearance of numerous highly organised forms of which we can find no trace of probable ancestors. Ammonites, Belemnites, Baculites, Hamites, Inocerami, Hippurites, and the remarkable reptilian Plesiosaurs, Ichthyosaurs, Pterodactyls, and monstrous Deinosaurs disappear as completely as if they had never existed, and their place is immediately filled by a congeries of highly developed placental mammals.

Many genera survived from the Mesozoic, but the organic hiatus is so complete that no single species higher in the scale than the primitive Foraminifera passed from the Cretaceous to the Tertiary.

Foraminifera are numerous throughout the whole of the Tertiary era and particularly abundant in the Middle and Upper Eocene; and the reef-building corals comparatively rare in the Chalk again become prominent in the Equatorial zones.

Brachiopods show a marked decline, except perhaps in the Australian waters; but marine Lamellibranchs and Gasteropods are more numerous than ever. Ammonites and Belemnites have disappeared, but *Nautilus* and gigantic *Aturia* are still common. Crustaceans are now represented by numerous short-tailed decapods.

Among the vertebrates we have a great array of fishes, as well as many sea-snakes, crocodiles, and birds. Placental mammals, including ancestral forms of most of the living ungulates (hoofed-herbivores), appear in the Lower Tertiary for the first time, and become prominent almost at once; and associated with them we have representatives of the non-placental marsupials which are still the dominant endemic mammals of the Australian continent.

Before the close of the Tertiary era there appeared the anthropoid apes, and finally man.

The flora is now dominated by the flowering Angiosperms, which are represented by a vast assemblage of monocotyledonous and dicotyledonous forms, which include the cactus, numerous palms, laurel, myrtle, magnolia, etc., comprising a luxuriant evergreen vegetation.

Rocks.—The sedimentary rocks of the Cainozoic era in the Northern facies are mostly incoherent sands, clays, and pebbly beds with subordinate layers of marls and hard, shelly limestones; but in the Southern or Equatorial facies of the Lower Tertiary hard limestones, sandstones, and shales predominate.

Marine and estuarine beds are largely represented, but deltaic, fluviatile, lacustrine, and desert deposits play an important *rôle* in all the Tertiary formations. Towards the close of the era, glacial accumulations are conspicuous in many temperate latitudes.

Generally speaking, the marine Tertiary deposits are marginal to the continental areas, and usually still lie horizontal, except where they have been involved in the structural folds of the great mountain-chains, or locally disturbed by volcanic outbursts.

Where the Tertiary systems are fully represented, they form a great succession of conformable strata; but where the succession is incomplete, there may be physical breaks of considerable magnitude. In England, for example, where the Miocene is entirely absent, the Pliocene rests unconformably on the Eocene and older rocks.

The volcanic activity which revived at the close of the Cretaceous after nearly an era of quiescence continued with periods of rest throughout the whole of the Cainozoic era. There is much evidence in favour of the belief that all great crustal movements have been preceded or accompanied by violent displays of volcanic activity.

Distribution.—The Tertiary systems are found in all parts of the globe; and in many regions there is a close geographical relationship between the Lower Tertiary formations and the Cretaceous. It would appear that many Cretaceous areas of deposition after a lapse of time became areas of deposition in the Tertiary era; and in regions where the Cretaceous rocks suffered little deformation, the Tertiary strata frequently rest on them with no visible appearance of stratigraphical discordance.

Tertiary sedimentary rocks are found involved in the folds of all the great mountain-chains of the globe, and from this we know that the Cainozoic has been the greatest mountain-building era of which we have any certain knowledge.

Rocks of Lower Tertiary age take part in the structure of the Alps, Apennines, Carpathians, Caucasus, Atlas, Himalayas, Andes, Rocky Mountains, Sierras, and many other great chains, all of which are therefore comparatively young. When we pause to remember that the site of a gigantic mountain complex such as the Himalayan was a sea-floor so recently as the Middle Tertiary, we begin to catch a faint conception of the comparative rapidity of great earth-movements and of the titanic forces of which they are the visible expression.

The uplift of the Tertiary rocks in some regions is enormous. In the Alps the Lower Tertiary Nummulitic Limestone occurs at a height of 11,000 feet above the sea, and in the Himalayas 17,000 feet.

Distribution of Land and Water.—The beginning of the Tertiary era still found the Tethys or Central Sea in existence, and on its floor and borders were laid down a great succession of Lower Tertiary deposits, including the Nummulitic Limestone. The Central Sea, as already described, extended from the Atlantic eastwards through the Mediterranean Basin, covered the whole of Southern Europe and North Africa and stretched over Asia Minor, Arabia, Persia, Baluchistan, Himalayan area to Further India; and although shrunken in size since the Cretaceous period, it still formed a great inland sea that girdled half the globe.

In the Middle Tertiary the eastern half of the Central Sea became occupied by the Himalayas, Caucasus, and the mountains of Persia, Arabia, and Asia Minor ; and its northern limits were curtailed by the rise of the Carpathians, Apennines, Alps, and Pyrenees.

The crustal corrugation and folding of the Himalayas, Alps, and other great chains continued until the close of the Miocene, when the Central Sea became broken up into disconnected inland seas and salt-water lakes.

In Pliocene and later times, due to the continued recession of the ocean, the Central Sea diminished in size until in our own time the Mediterranean Sea is all that now remains to mark its former existence.

The present distribution of animals and plants tends to show that there was a Tertiary land connection between Europe and North America through the Faroe Islands and Iceland, and between Alaska and North-East Asia across the present Behring Straits. About the same time land-bridges probably joined South Africa, South America, New Zealand, and Australia with the Antarctic continent.

It is a singular fact that the Tertiary mollusca of Chile presents a greater resemblance to the living and fossil mollusca of the Mediterranean Basin than to the mollusca now living on the coast of Chile. The inference to be drawn from this is that the isolation of the Chilian region did not take place till some time between the mid-Tertiary and the beginning of the Pleistocene.

Climate.—The Tertiary climate of Europe and North America was at first warm, and then tropical ; but gradually the temperature became cooler, and at last Arctic cold prevailed. This last phase took place in quite late Tertiary times, and has since been succeeded by a cold temperate climate.

Similar variations of climate also took place in the Southern Hemisphere.

The changes of climate are indicated by the character of the land animals and plants, and to some extent by the marine faunas. The period of refrigeration witnessed a great advance of the polar ice-sheets, and the accumulation of gigantic glaciers on the higher mountain-chains.

Subdivision.—In the Cainozoic era, climate exercises a more potent influence than ever in the distribution of animals and plants ; and in consequence the methods of subdivision and correlation of rock-formations by some characteristic fossils so successfully applied to the Mesozoic and Palæozoic systems can no longer be employed. In these circumstances it became necessary to devise some new method of subdivision in order that the formations in one region should be equivalent in time to those in another region.

The method of classification first suggested in 1830 by the French geologist Deshayes, and subsequently adopted by Lyell, for the chronological subdivision of the Cainozoic rock-formations is based on the proportion of living to extinct forms contained in the complete fauna. The principle underlying this method is that the older a formation is, the fewer living species will it contain; and the younger it is, the greater the number.

The percentage method of classification has proved accurate, and is commonly adopted.

When groups of beds in two distant regions are classified as Eocene, it does not necessarily follow that they are contemporaneous, for it is evident that through various physical and climatic conditions a larger proportion of species may contrive to survive in one region than in another. Moreover, the rate of evolution is not the same in the different orders of the animal kingdom.

The age of formations, as determined by the percentage of living species, is comparative rather than actual; hence the correlation of distant, disconnected groups of beds by this method is never satisfactory without supporting evidence.

The main divisions of the Cainozoic, or *Neozoic*[1] era as it is sometimes called, are as follow:—

Upper Cainozoic or Neogene	6. Recent.	
	5. Pleistocene[2]	=mostly recent species.
	4. Pliocene[3]	=majority recent species.
	3. Miocene[4]	=minority recent species.
Lower Cainozoic or Palæogene	2. Oligocene[5]	=few recent species.
	1. Eocene[6]	=dawn of recent species.

The Foraminifera are such persistent organic types that, standing by themselves, they are of little value for the division of the Cainozoic era into time periods; while the higher land vertebrates show such a rapid biological development and limited distribution, combined with a constitution so acutely sensitive to climatic and geographical changes, that they are as untrustworthy for purposes of subdivision. The more stable and wide-spread marine mollusca form the best available basis of classification.

The percentages of living, *i.e.* recent, species of the molluscous fauna used as a basis of classification are as follow:—

---

[1] Gr. *neos*=new, and *zoe*=life.

[2] Gr. *pleiston*=the most, and *kainos* (*cene*)=recent.

[3] Gr. *pleion*=more, and *kainos*=recent.

[4] Gr. *meion*=less, and *kainos*=recent.

[5] Gr. *oligos*=few, and *kainos*=recent.

[6] Gr. *eos*=the dawn, and *kainos*=recent.

Recent = 100 per cent.
Pleistocene = 90—100 per cent.
Pliocene = 40— 90 per cent.
Miocene = 10— 40 per cent.
Eocene = 0— 10 per cent.

The main divisions of the Cainozoic are sometimes recognised as separate systems, but they represent periods of time so much shorter than the systems of the Palæozoic and Mesozoic eras that they are, by some writers, grouped into two great divisions or systems called the *Palæogene* and *Neogene*. Since the systems are admittedly of unequal value as measurers of time, it is unimportant whether we regard the Eocene, Oligocene, etc., as systems or merely as series. Obviously the relative importance of a succession of strata cannot be measured by the thickness of the deposits which it comprises, but by the organic changes which took place during the time occupied in the deposition of the sediments.

Although the Cainozoic may cover a relatively short period of time, it is certain that it has witnessed a more striking and momentous development of organic life and physical changes of greater magnitude than the Mesozoic. Hence, for our present purpose, we will regard the Cainozoic as an era and the main divisions as systems.

EOCENE SYSTEM.

At the close of the Cretaceous there was a recession of the sea all over the globe. Hence the Eocene deposits occupy a smaller area than the Cretaceous; and shallow water, estuarine and even terrestrial sediments follow the Chalk.

The recession of the sea caused a widespread migration of the Cretaceous life, and none survived until the Eocene. All the forms slowly disappeared or became modified by the development of structural features better adapted to the new conditions and environment.

Distribution.—In Europe the Eocene is mainly distributed in two geographical regions: the *Anglo-Gallic*, which embraces South England, North France, and Belgium; and the *Alpine* or *Mediterranean*, which in the main follows the former limits of the Central Sea and embraces the whole of Southern Europe and North Africa and a wide zone extending eastward to Further India.

Rocks.—In the Anglo-Gallic region, which at one time spread over a large portion of North-West Europe, the rocks of the Eocene System are mainly loose incoherent sands, clays, and pebbly beds with occasional bands of hard shelly limestone, and in the Alpine region, massive beds of hard limestone, compact sandstones, and shales. The limestones of this region are largely composed of *Nummulites*.

The Nummulites are the most complex and most highly organised of all the Foraminifera. A few appeared in the Jurassic and Cretaceous, but their maximum development took place in the Middle Eocene. They are equatorial in habitat, and lived in the Great Centre Sea (Tethys) in extraordinary profusion. They are unknown in the Tertiary rocks of Australia, New Zealand, South Africa, and America.

In the Swiss and Maritime Alps, in the Apennines, Carpathians, and eastwards to the Himalayas, the Upper Eocene is also represented by an extraordinary thickness of grey sandstones and shales of the *Flysch* facies. These rocks occur in close association with massive beds of the nummulitic limestone, but are themselves practically devoid of all organic remains. The same facies of rocks is also largely developed in California.

The volcanic activity which revived at the close of the Cretaceous continued into the Eocene. The outbursts were local and intermittent. Eocene volcanic rocks occur in North Ireland, West Scotland, Faroe Islands, Iceland, Greenland, and in the States of California, Oregon, Washington, Montana, Wyoming, and Colorado.

British Isles.

The Eocene deposits of England occupy two triangular areas in the south-east end of the island, namely, the *London Basin* in the Thames Valley, and the *Hampshire Basin*, with its base lying along the coast of the mainland opposite the Isle of Wight. Outliers occur on the Isle of Wight, Salisbury Plain, Chilterns, and elsewhere, and indicate a former extension of the Eocene strata over the whole of South-East England.

The Eocene beds everywhere rest on the Chalk, usually without any visible stratigraphical unconformity.

The beds of the London and Hampshire basins exhibit a close relationship both in fauna and lithological sequences, and it is certain that, although now separated by a ridge of chalk, they were all laid down on the floor of the same continuous sea.

Local Subdivisions.—The subdivisions usually recognised in the two basins are as follow :—

	London Basin.	Hampshire Basin.
Upper Eocene	6. Upper Bagshot Sands.	Barton Beds.
	5. Middle Bagshot Sands.	Bracklesham Beds.
	4. Lower Bagshot Sands.	Lower Bagshot Beds.
Lower Eocene	3. London Clay.	London Clay.
	2. Woolwich and Reading Beds.	Reading Beds.
	1. Thanet Sands.	(Absent.)

The **Thanet Sands** consist of light-coloured sands which are clayey at the base, and contain glauconitic grains. Where they rest on the Chalk, they contain a basal layer of unworn, green-coated flints, which was apparently formed after the sands were deposited. The flints are the insoluble residuum left behind after the upper layers of Chalk in which they were imbedded had been removed by the action of percolating water. Examples of underground chemical erosion are not infrequent where limestones are followed by porous sands or sandstones containing moving water.

The fossils of the Thanet Sands are marine and mostly Lamellibranchs and Gasteropods. Among the more abundant forms are *Corbula regulbiensis* and *Aporrhais Sowerbyi* (Plate LV., fig. 3).

The **Woolwich** and **Reading Beds** vary considerably in character. In East Kent they consist of marine sands, and in West Kent and Surrey of estuarine sands and grey clays, which may be taken as an indication that the land lay to the westward.

FIG. 219A.—Section across the Isle of Wight. (After H. W. Bristow.)

a. Chalk.—Cretaceous.
b. Reading Beds.
c. London Clay.
d. Lower Bagshot Beds.
e. Bracklesham Beds.
f. Barton Clay.
g. Barton Sand.
} Eocene.

h. Headon Beds.
i. Osborne Beds.
k. Bembridge and Hamstead Beds.
} Oligocene.
m. Gravels.—Recent.

In the Hampshire Basin, only the Reading Sands are present. The *Oldhaven* and *Blackheath Beds*, which consist of fluviatile pebbly sands and pebbles, are local subdivisions overlying the Woolwich Series.

The **London Clay** is perhaps the most important division of the Eocene in England. It is usually a stiff marine clay of a bluish-grey colour, except at the surface where it weathers to a brown hue. It contains layers of calcareous concretions and nodules of pyrites. In some places crystals of selenite are common. At London, which lies about the centre of the basin, the thickness of the clay is 400 or 500 feet. In the Hampshire Basin the London Clay is more sandy than in the eastern basin.

Fossils are abundant and mostly marine molluscs, crustaceans, fishes, and land plants. Among the molluscs are *Aporrhais Sowerbyi* and *Aturia ziczac*; and the genera *Pleurotoma*, *Fusus*, *Murex*, and *Natica* are represented by numerous species.

The fishes include many forms of rays (*Myliobates*), and the ubiquitous sharks (*Lamna, Otodus,* etc.). Among the numerous reptilians are turtles, tortoises, crocodiles, and a sea-snake. The remains of several birds have also been found. The mammals include ancestral forms of the tapir, bat, and opossum.

The plants include fan-palms, feather-palms, cactus, fig, elm, poplar, beech, planes, maple, and many other angiosperms.

The land animals and vegetation would indicate the prevalence in the Middle Eocene of a warm, temperate, or semi-tropical climate in the south of England resembling that of New Zealand at the present time.

The **Bagshot Beds** are divided into three subdivisions, Lower, Middle, and Upper. They occupy a smaller area than the London Clay, which is probably a result of denudation. The Upper and Lower divisions consist mainly of sandy beds, and the Middle division, of clays. In the London Basin they do not contain many fossils, but the corresponding beds in the Hampshire Basin—the Bracklesham Beds on the coast of Sussex, and Barton Beds in the Isle of Wight—contain a rich molluscous fauna which includes *Cardita sulcata* (Plate LV., fig. 12), *Crassatella sulcata* (Plate LV., fig. 11), *Voluta ambigua* (Plate LV., fig. 7), *V. athleta* (Plate LV., fig. 8), and *Pleurotoma dentata.*

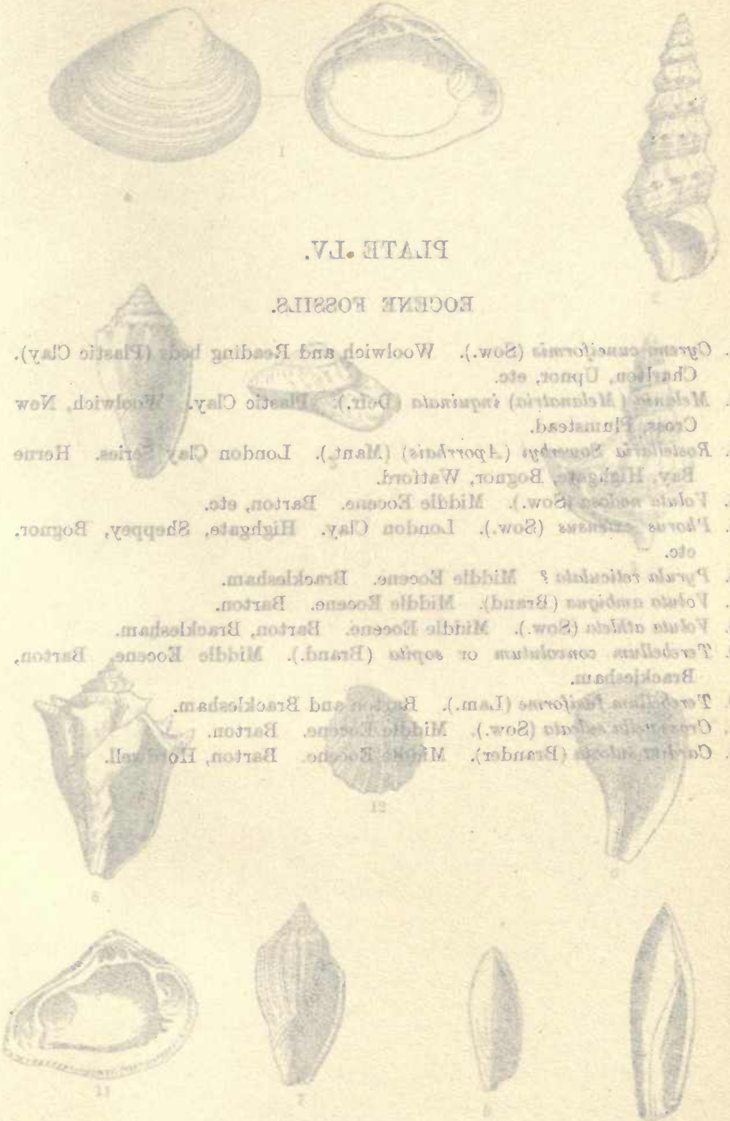
The well-known *Grey Wethers* of the south of England are tabular masses of siliceous cement-stone, probably derived from portions of the Bagshot sands solidified by the infiltration of siliceous waters.

Bovey Tracey Beds.—These beds consist of a series of gravels, sands, and clays with seams of lignite lying in an old lake-basin in the valley of the Teign, between Newton Abbey and Bovey Tracey, in Devonshire. They rest on a highly eroded surface of the Devonian and Carboniferous rocks.

This series of lacustrine sediments varies from 200 to 300 feet thick; and is interesting as representing the continental facies of the Aquitanian in South England.

The fossil plants are numerous and frequently well preserved. They show that the adjacent lands at the close of the Oligocene were clothed with luxuriant subtropical evergreen forests. Among the species are ferns, including *Osmunda* and numerous angiosperms, represented by *Sequoia,* spindle-trees, cinnamon, oak, fig, laurel, willow, and vines.

Contemporaneous Volcanic Activity.—At the time the streams and rivers were discharging their load of detritus into the Anglo-Gallic sea and its estuaries, there was a great display of volcanic activity in the north of Ireland and west coast of Scotland. Successive sheets of lava were poured over the land and formed wide basaltic plateaux.



EOCENE FOSSILS.

PLATE LV.

EOCENE FOSSILS.

1. *Cyrena cuneiformis* (Sow.). Woolwich and Reading beds (Plastic Clay). Charlton, Upnor, etc.
2. *Melania* (*Melanatria*) *inquinata* (Defr.). Plastic Clay. Woolwich, New Cross, Plumstead.
3. *Rostellaria Sowerbyi* (*Aporrhais*) (Mant.). London Clay Series. Herne Bay, Highgate, Bognor, Watford.
4. *Voluta nodosa* (Sow.). Middle Eocene. Barton, etc.
5. *Phorus extensus* (Sow.). London Clay. Highgate, Sheppey, Bognor, etc.
6. *Pyrula reticulata ?* Middle Eocene. Bracklesham.
7. *Voluta ambigua* (Brand). Middle Eocene. Barton.
8. *Voluta athleta* (Sow.). Middle Eocene. Barton, Bracklesham.
9. *Terebellum convolutum* or *sopita* (Brand.). Middle Eocene. Barton, Bracklesham.
10. *Terebellum fusiforme* (Lam.). Barton and Bracklesham.
11. *Crassatella sulcata* (Sow.). Middle Eocene. Barton.
12. *Cardita sulcata* (Brander). Middle Eocene. Barton, Hordwell.

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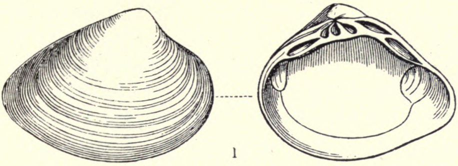
[PLATE LV.



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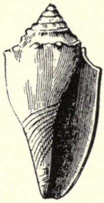

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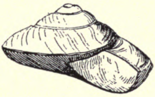

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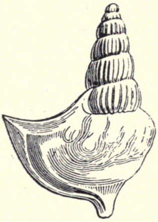

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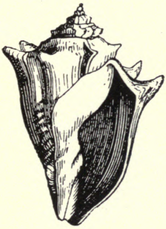

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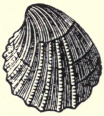

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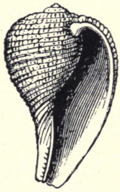

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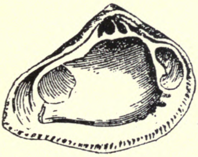

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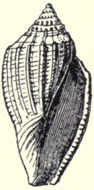

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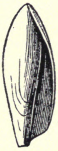

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EOCENE FOSSILS.

The Antrim Plateau, which is but the remnant of a greater plateau, extends from Belfast Lough to Lough Foyle, and from the south of Lough Neagh to the Giant's Causeway, and covers an area of about two thousand square miles. The great cliffs which form the striking coastal scenery of the famous Giant's Causeway have been carved out of the edge of a thick sheet of basalt, which exhibits a symmetrical columnar structure of great beauty (fig. 125).

From Antrim the basalts extend to the Islands of Staffa, Mull, Skye, and the other islands of the Inner Hebrides. At Staffa they form the celebrated Fingal's Cave.

These basalts were poured out by successive eruptions, some of which were separated by considerable intervals of quiescence. In these periods of rest subaerial denudation became active, and the neighbouring hollows and lagoons were soon filled with sands and gravels. The surface of the lava-flows also became weathered and disintegrated, and formed soils on which a rank semi-tropical vegetation grew long enough to form peaty deposits that have since become changed into beds of lignite. Later eruptions overwhelmed the forests and covered up the newly formed sediments and peat-bogs.

The plant remains enclosed in the intercalated soils and detrital material comprise various palms, cactus, oak, laurel, and other evergreen trees found in the London Clay.

It is claimed by some writers that the volcanic region of North Ireland and West Scotland belongs to the petrographical province which includes the Faroe Islands, Iceland, and the eastern portion of Greenland.

Eocene of Other Countries.

France.—The Eocene System is very fully developed in the Paris Tertiary Basin, which is a continuation of the English basins across the Channel. The deposits are mainly marine, but beds of estuarine and freshwater deposits are also present. Molluscs are exceedingly abundant; and the genera *Fusus*, *Pleurotoma*, and *Cerithium* are represented by the greatest number of species.

French geologists recognise three divisions, namely, the Lower, Middle, and Upper.

The *Lower Eocene* consists mainly of estuarine and terrestrial marls, sands, and plastic clay with seams of brown coal.

The *Middle Eocene* is represented by a band of impure shelly limestone, 30 feet thick. This is the principal building-stone in Paris, and hence has become the best-known member of the Eocene in this basin. The lower beds of the limestone contain Nummulites in great abundance; also many sea-urchins and a great assemblage of Lamellibranchs and Gasteropods. Among the last is the gigantic *Cerithium giganteum* (Plate LVI., fig. 1), which sometimes reaches a length of nearly three feet.

The *Upper Eocene* is a marine sand about 48 feet thick, crowded with molluscs. It is intercalated at St Ouen with a band of freshwater limestone which contains a great many examples of *Limnæa longiscata*.

Belgium.—The Eocene rocks of Belgium show a similar development to those of the London and Paris Basins, to which they are closely related. The lowest beds at Mons contain *Cidaris Tombecki* and other Cretaceous sea-urchins.

Southern Europe.—The Eocene deposits laid down on the floor of the great Central Sea extend from Portugal eastward through the Alps, Apennines, Carpathians, and Caucasus to Asia Minor, whence they pass still further east to the Himalayas. On the south side of the Mediterranean they stretch from the Atlas Mountains and Morocco eastwards to Egypt, Libyan Desert, Syria, Palestine, Arabia, and Persia, where they merge into the broad zone passing through Central Asia.

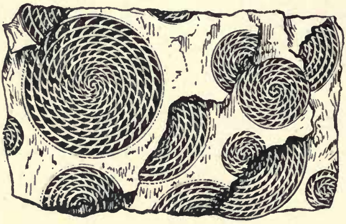
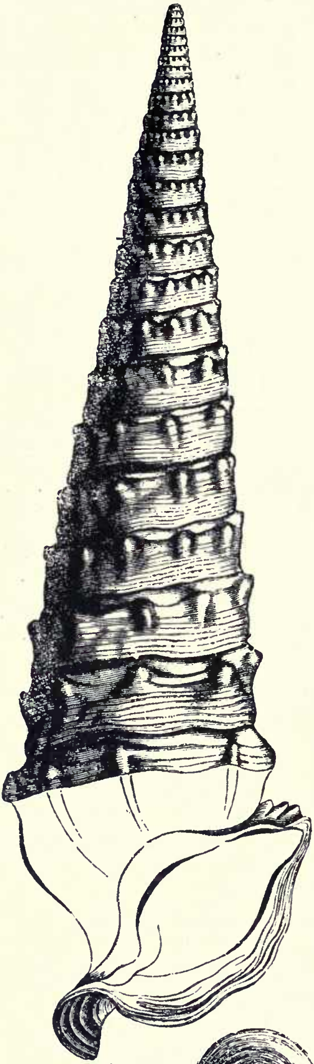


FIG. 220.—Fragment of Nummulitic Limestone.

The deposits laid down in this great inland sea belong to the Alpine or Equatorial facies, and differ vastly from those of the Northern facies as developed in the Anglo-Gallic region. In the first place, the rocks are not loose and incoherent, but mainly masses of compact limestone or hard sandstones and gritty shales of the *Flysch* type. Palæontologically they are characterised by the abundance of Nummulites, which are large disc-shaped Foraminifera provided with a complicated chambered shell.

The Nummulitic Limestone of Upper Eocene age consists of a series of beds of massive limestone, in places 3000 feet thick. It can be traced from the Pyrenees eastwards through the Alps, Carpathians, and Balkan States to Asia Minor. On the south side of the Mediterranean, it stretches far south into the Sahara, Libyan Desert, and Egypt. From Arabia and Asia Minor, as already described, it passes eastward to the Himalayas and



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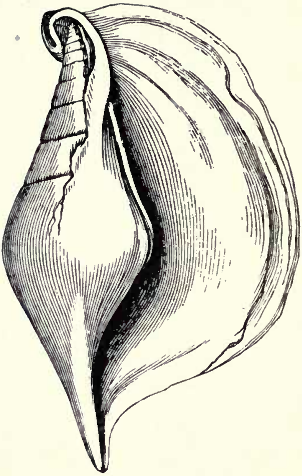

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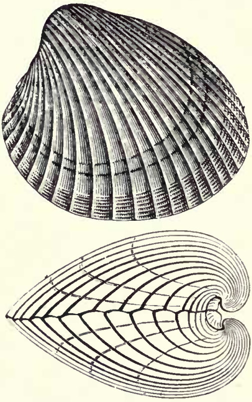

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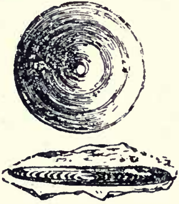

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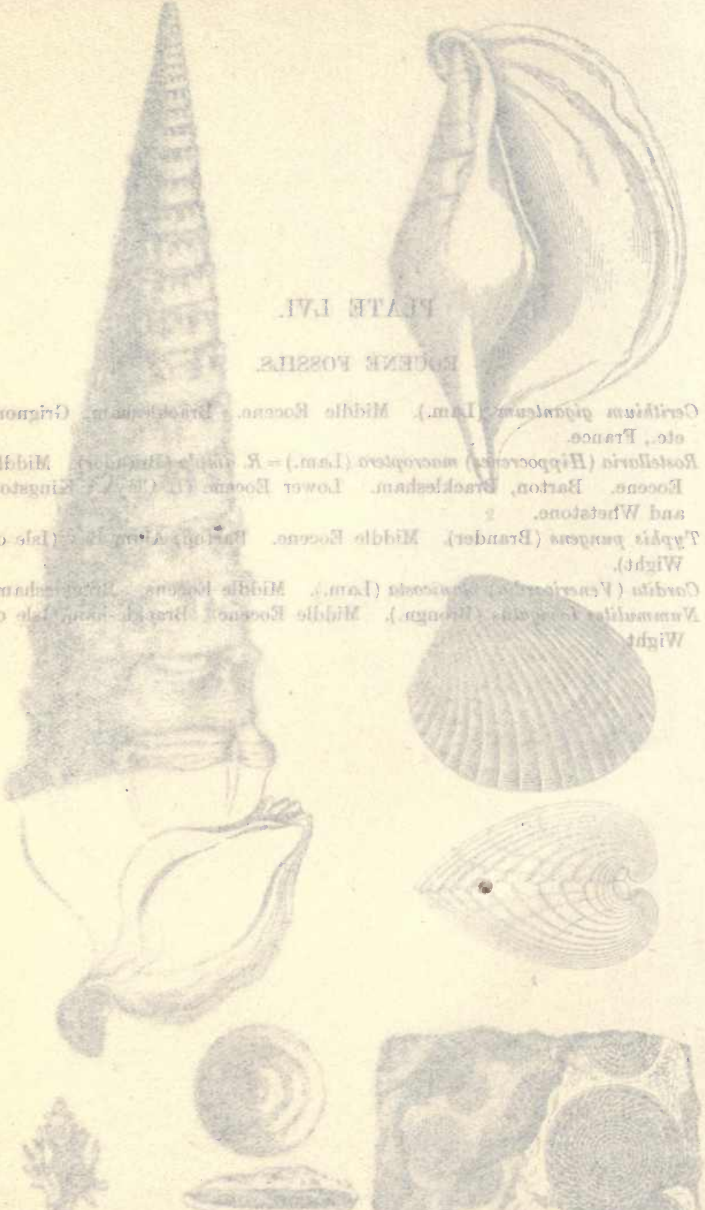
EOCENE FOSSILS.

PLATE LVI.

EOCENE FOSSILS.

1. *Cerithium giganteum* (Lam.). Middle Eocene. Bracklesham, Grignon, etc., France.
2. *Rostellaria* (*Hippocrenes*) *macroptera* (Lam.) = *R. ampla* (Brander). Middle Eocene. Barton, Bracklesham. Lower Eocene (L. Clay). Kingston and Whetstone.
3. *Typhis pungens* (Brander). Middle Eocene. Barton, Alum Bay (Isle of Wight).
4. *Cardita* (*Venericardia*) *planicosta* (Lam.). Middle Eocene. Bracklesham.
5. *Nummulites lævigatus* (Brongn.). Middle Eocene. Bracklesham, Isle of Wight.



EOCENE FOSSILS.

Further India, and thence through Java, Sumatra, Borneo, and Philippines. In Egypt it was the chief source of the building-stone used in the construction of the Pyramids, near Cairo.

India.—The Eocene of India belongs, as we have seen, to the Southern or Equatorial facies, and was laid down in the eastern end of the Central Sea. It is principally characterised by the great development of the nummulitic limestones.

The Eocene of India is divided into three stages or series:—

Upper Eocene (3)—Khirthar Series.
Middle Eocene (2)—Laki ,,
Lower Eocene (1)—Ranikot ,,

The *Ranikot Series* consists mainly of basal fluviatile sandstones followed by marine beds. It is restricted to a small area in Scind.

The *Laki Series* is in some places sandy, in others calcareous. The well-known Laki Limestone abounds in Foraminifera, of which the genera *Nummulites* and *Alveolina* are prominent. This series is of great economic importance for its valuable coal-seams, which are well developed in the Punjab, Assam, and Baluchistan.

The *Khirthar Series* consists chiefly of limestones which, on the Scind-Baluchistan border, attain a thickness of 3000 feet, and contain some zones remarkably rich in Nummulites, among which *Nummulites lævigatus* (Plate LVI., fig. 5), *N. perforatus*, and *N. complanata* are the most common.

North America.—Rocks of Eocene age cover large tracts in the United States, and in the main follow the outcrops of the Cretaceous, although they occupy a much smaller area as a result of the recession of the sea which followed the close of the Cretaceous.

They comprise three distinct types of deposits, each occupying a separate geographical region. The marine type is distributed as a fringe along the Atlantic border and Gulf of Mexico; the brackish-water occurs mainly in Washington and Oregon; and the freshwater or lacustrine occupies old lake-basins among the mountains of the Western States.

The marine Eocene beds are typically developed in the Gulf region, and are perhaps best displayed in the State of Alabama, where three divisions are recognised, each richly fossiliferous.

The Eocene beds of Texas are mainly estuarine and partly terrestrial, the latter facies interstratified with layers of salt and gypsum-bearing sediments and seams of lignite. From Texas these beds extend northwards to Arkansas.

The Puget Sound coal-bearing series of Washington is estuarine and terrestrial. It attains a thickness variously estimated at from 10,000 to 20,000 feet.

Numerous patches of coal-bearing strata of Eocene age, usually much disturbed, are scattered around the coastal fringe and maritime valleys of Alaska.

The marine fauna of the North American Eocene System is remarkably rich in molluscs, among which Lamellibranchs and Gasteropods largely predominate. But the most notable feature of this period is the sudden appearance of numerous placental mammals, many of which possess structural features that seem to connect them with the placentals of the present day.

Among the primitive types of land placentals have been found what are believed to be ancestral forms of the rhinoceros, deer, horse, tapir, cat, dog, otter, badger, etc.

The Eocene seas were also peopled with the earliest marine mammals, the cetaceans being represented by whales (Zeuglodons), dolphins, and porpoises; the sirenians by the dugong; and the pinnipeds by seals and sea-lions.

The Eocene vegetation, as in Europe, indicates a temperate climate in the early part of the period, followed by semi-tropical conditions in the Middle and Upper Eocene.

It is noteworthy that many of the leading types of plant life in the Eocene of North America and Europe are allied to types that still survive in India and Australia.

Australasia.—Marine deposits of Eocene age are unknown throughout Eastern Australia, but are well developed at Mount Gambier and Murray Flats in South Australia, where they contain a rich fauna which includes numerous corals, sea-urchins, brachiopods, Lamellibranchs, and Gasteropods, as well as the remains of fishes and cetaceans.

Eocene deposits are well developed in Tasmania and New Zealand. In the latter they contain seams of bituminous coal of great economic value.

OLIGOCENE SYSTEM.

The Oligocene System was formerly regarded as the uppermost portion of the Eocene, with which it is always intimately connected where the full Lower Tertiary succession is present. In this case the condominion is perfect. The separation has no palæontological or lithological basis, and was mainly made in deference to geographical considerations.

In South England, where the Eocene is so well developed, the Oligocene is poorly developed and the Miocene is altogether absent; but in Germany, where the Eocene is absent, the Oligocene is an important formation. From this we learn that considerable geographical changes took place in North-West Europe at the close of the Eocene. South-East England and North France, which were then covered by the sea, became dry land, and Germany, which was dry land, became inundated by the sea. The uplift in England was balanced by subsidence in Germany.

It was principally owing to these changes of land and sea that it was considered convenient to separate the Oligocene from the Eocene in England and Continental Europe. The Oligocene is not a natural division; and in regions outside Europe where the marine Tertiary succession is complete, the formations arrange themselves into the three natural divisions, Eocene, Miocene, and Pliocene.

Distribution.—Except in Germany where the Lowest Tertiary beds are absent, the Oligocene occupies the same areas as the Eocene. In Europe it occurs in two distinct geographical provinces, namely, the Northern and the Southern.

The Northern Province embraces the greater portion of the Anglo-Gallic basin, and the whole of Germany except the Alpine portion.

The Southern Province covers the region now occupied by the Alps, Apennines, and Carpathians.

In the Northern Province the sediments, as in the Eocene, are mainly represented by loose sands, clays, and pebbly beds with thin-bedded limestones; and in the Southern by sandstones and shales of the Flysch type, together with massive beds of soft pebbly sandstones and coarse conglomerates, which constitute the series of deposits called *Molasse* by Swiss geologists. The lower portion of the Molasse, called *Older Molasse*, is referred to the Oligocene, and the upper portion to the Miocene.

From the Carpathians eastwards through the Balkans, Asia Minor, Arabia, Persia, Baluchistan, the Himalayas, and Burma, the Oligocene is co-extensive with the Eocene.

In Baluchistan and Scind, the strata are mainly unfossiliferous shales of the Flysch facies, and massive beds of nummulitic and coralline limestones.

In North America the Oligocene has not been separated from the Eocene.

British Isles.

The Oligocene strata play an unimportant part in Britain, and are confined to a small area in the Isle of Wight and Hampshire Basin, where they rest conformably on the Eocene. They are not represented in the London Basin.

The deposits consist mainly of sand, clays, marls, and thin-bedded limestones, and they are partly marine, partly estuarine, and partly freshwater. They were obviously laid down in the

Hampshire Eocene delta at a time when distinct but inconsiderable oscillations of the land were in progress.

The subdivisions or stages of the Oligocene of South England are as follow :—

Oligocene	4. Hamstead Beds.
	3. Bembridge Beds.
	2. Osborne Beds.
	1. Headon Beds.

Marine Beds are intercalated with the Headon, Bembridge, and Hamstead Beds. The remaining beds are mainly deltaic and freshwater. In the Headon Beds there occur seams of lignite.

Fossils are found in all the different divisions, and are abundant on some horizons.

The land snails include *Helix* and *Amphidromus* ; and among the common forms of pond and river molluscs are the Lamellibranchs *Unio* and *Cyrena* ; and of the Gasteropods *Viviparus*, *Limnæa*, and *Planorbis*.

The fossil vertebrates include the remains of rays (*Myliobates*), sea-snakes, crocodiles, alligators, turtles, and a whale (*Balænoptera*).

The Bembridge Beds have yielded the bones of many mammals, including those of the pachyderms *Palæotherium*,[1] *Anoplotherium*,[2] *Hyopotamus*,[3] and *Chæropotamus*.

The fossil plants are mostly subtropical evergreens, such as fan-palms, feather-palms, conifers, oaks, laurels, and vines.

The nucules of *Chara* (Plate LVII., fig. 11), a freshwater alga, are plentiful in the Bembridge Limestone in the Isle of Wight.

The marine and brackish-water beds contain *Ostrea*, *Cyrena*, *Cytherea*, *Cerithium*, *Melania*, and many other molluscs. Of the Middle Headon division *Cytherea incrassata* is the characteristic fossil, and *Ostrea velata* forms thick beds. In the Osborne Beds *Melania excavata* is a common form.

Continental Europe.

The Oligocene is fully developed in the Paris Basin, where only the middle division is marine ; in Belgium, where the strata consists of alternations of marine and freshwater deposits ; and in North Germany, where the beds are essentially marine.

Among the fossils, land, freshwater, estuarine, and marine molluscs are plentiful, and also the remains of plants, fishes, and mammals.

The *Lower Oligocene* of the Paris Basin is characterised by

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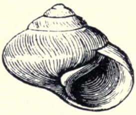
[1] Gr. *palaios*=ancient, and *therion*=an animal.

[2] Gr. *anaplos*=unarmed, and *therion*=an animal.

[3] Gr. *hus*=a log, and *potamus*=a river.



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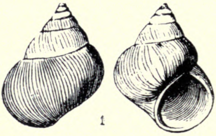

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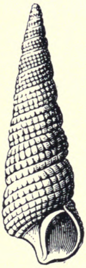

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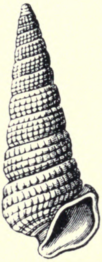

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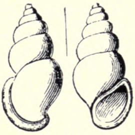

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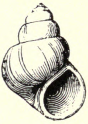

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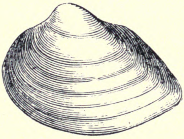

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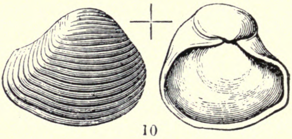

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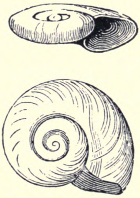

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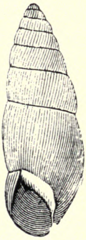


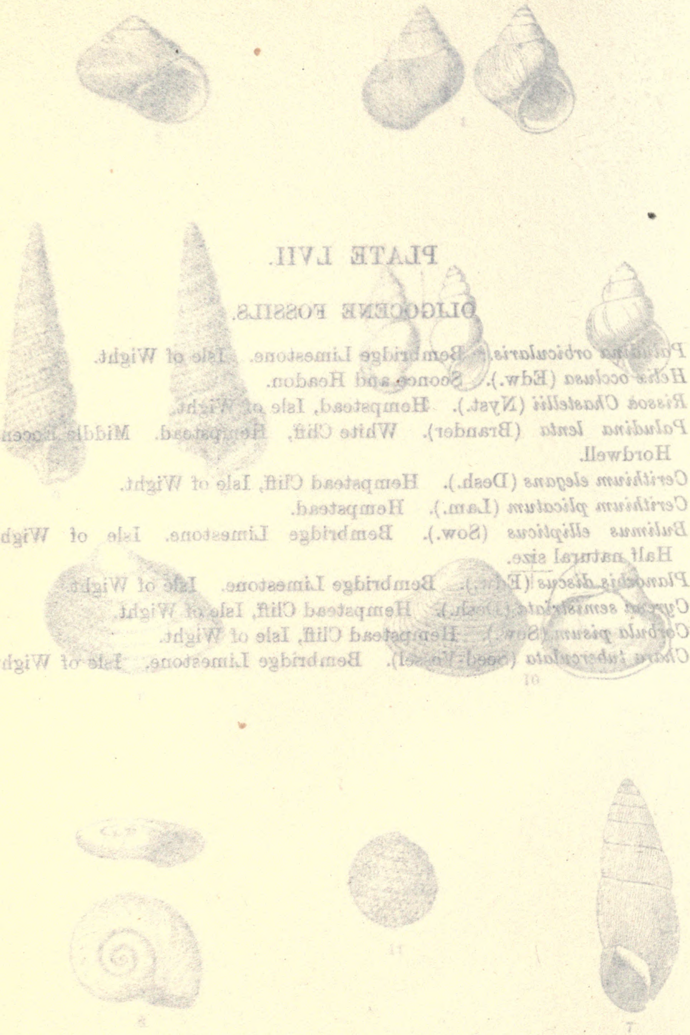
7

Oligocene Fossils.

PLATE LVII.

OLIGOCENE FOSSILS.

1. *Paludina orbicularis.* Bembridge Limestone. Isle of Wight.
2. *Helix occlusa* (Edw.). Sconce and Headon.
3. *Rissoa Chastellii* (Nyst.). Hempstead, Isle of Wight.
4. *Paludina lenta* (Brander). White Cliff, Hempstead. Middle Eocene. Hordwell.
5. *Cerithium elegans* (Desh.). Hempstead Cliff, Isle of Wight.
6. *Cerithium plicatum* (Lam.). Hempstead.
7. *Bulimus ellipticus* (Sow.). Bembridge Limestone. Isle of Wight. Half natural size.
8. *Planorbis discus* (Edw.). Bembridge Limestone. Isle of Wight.
9. *Cyrena semistriata* (Desh.). Hempstead Cliff, Isle of Wight.
10. *Corbula pisum* (Sow.). Hempstead Cliff, Isle of Wight.
11. *Chara tuberculata* (Seed-Vessel). Bembridge Limestone. Isle of Wight.



OLIGOCENE FOSSILS.

mammalian remains, which include *Palæotherium*, *Anoplotherium*, etc.; first described by Cuvier.

The *Middle Oligocene* of the Paris Basin and Rhine Valley contains a rich fauna, which includes *Cerithium plicatum* (Plate LVII., fig. 6), *Buccinum cassidaria*, *Cyrena semistriata*, and *Leda Deshayesiana*. The last is also characteristic of the *Septaria Clay*, which is a well-marked member of the German Middle Oligocene.

The Upper Oligocene of the Paris Basin is freshwater, and contains numerous species of *Helix*, *Viviparus*, *Planorbis*, and *Limnæa*. The marine equivalent of these beds in the Mainz Basin of the Rhine Valley contains *Cerithium plicatum*, *Perna Soldani*, and other molluscs.

The Flysch sandstones and shales of the Southern European Province are practically unfossiliferous, but contain at Glarus a bed of slaty shale crowded with well-preserved fish remains.

The *Molasse Series* of Switzerland rises into high picturesque mountains, as in the Rigi and Rossland. It consists essentially of fluviatile drifts discharged into a freshwater lake-basin. In many places its sediments have preserved numerous remains of the vegetation which clothed the slopes of the surrounding ranges. Curiously enough, the plants include palms related to an American type, the Californian conifer *Sequoia*, as well as the alder, fig, cinnamon, oak, and many other evergreen forest trees.

The geographical names usually applied to the Oligocene of France, Belgium, Switzerland, North Italy, and regions where that system has been recognised are as follow:—

Upper Oligocene—3. Aquitanian, so named from Aquitania.
Middle Oligocene—2. Stampian, ,, Étampes.
Lower Oligocene—1. Tongrian, ,, Tongres in Limbourg.

Perhaps the most interesting Oligocene deposits in Europe are the amber-bearing beds near Königsberg in Pomerania. The lower beds consist of glauconitic sands with a rich Lower Oligocene fauna, which includes molluscs, sea-urchins, numerous crustaceans, and the teeth of sharks; and the upper beds of lignite-bearing sands.

The amber for which these beds have long been famous is the fossil resin of various pines, especially of *Pinus succinifera*. It is found in what is locally called the *Blue Earth*, not far from the base of the glauconitic sands.

The scientific importance of the amber depends on the remarkable number of insects, spiders, etc., and plant remains enclosed in it, usually in a perfect state of preservation. Altogether over 2000 species of insects; and of plants, over 100 Dicotyledons alone have been identified; also palms and other Monocotyledons.

India.

The Oligocene is represented in Baluchistan by the Kojak Shales of the Flysch facies, and in Scind and Baluchistan by massive beds of fossiliferous marine strata, which are divided into two series, the *Nari* and *Gaj* :—

Lower Miocene	3. Mekran.
Oligocene	2. Gaj.
	1. Nari.

The Nari Series includes massive beds of Nummulitic Limestone, which are particularly rich in large Foraminifera, some of which attain a diameter of several inches.

The *Gaj Series* consists of shales and coral limestones.

Origin of the Flysch Facies of Deposits.

Deposits of the Flysch type are conspicuous in the structure of the Alps, Carpathians, Caucasus, and mountain systems of Persia, Baluchistan, and Northern India.

They consist of alternating grey sandstones and gritty shales, or simply of shales alone, and are everywhere conspicuously unfossiliferous. Bands of fossiliferous calcareous strata are in a few places intersected with them, and in the adjacent areas they are frequently associated with massive beds of marine limestones.

The Flysch Series comprises a pile of strata which ranges in age from the Upper Cretaceous to the Oligocene. They are obviously composed of deltaic detritus that accumulated on the borders of the Central Sea at the mouths of the rivers draining the great northern continent. The detritus was not spread out as a continuous sheet along the shores of the Central Sea, but was piled up to a great thickness in the deltaic areas. At its outward fringes the material was in places intercalated with thin sheets of marine sediments.

In the clearer and deeper waters of the adjacent parts of the Central Sea there also accumulated, contemporaneously with the deltaic sediments, the thick deposits of calcareous sediments, which now form the massive beds of Nummulitic Limestone so conspicuous in the Alps, Carpathians, Baluchistan, and Himalayas.

The character of the sediments composing the Flysch Series, and the absence of organic remains, would tend to show that there was a considerable rainfall all over the northern continent, attended with rapid denudation of the land, and a correspondingly rapid accumulation of fluviatile detritus—so rapid as to preclude the existence of living organisms within the area of deposition.

The total thickness of the Flysch sandstones and shales has been variously estimated at from 10,000 to 20,000 feet; but the thickness of sediments of this character cannot be determined by measurements taken across the apparent bedding planes.

When detrital material is shot into comparatively deep water, as the reclamation of the fringe of the basin proceeds, it is pushed further and further into the basin, each successive layer assuming its proper angle of rest. With the constant recurrence of floods, sands and muds overspread and succeed one another in a pile of alternating sheets.

When fluviatile deposition of this kind begins on a sea-littoral where marine deposition has previously been in progress, the first layers of fluviatile detritus discharged into the sea are laid down parallel with the bedding-planes of the marine deposits; but whenever the filling in has been carried forward so far that there is a sudden drop into deep water, the bedding-plane of the detritus becomes parallel with the angle of rest assumed by the material as it falls over the end of the advancing delta.

The sediments laid down in the shallow waters of the delta are horizontal or possess a gentle slope seaward, but those discharged in the deeper waters at the outer edge of the delta assume an angle of 30° or more. It should, however, be noted that it is only where the accumulation of fluviatile detritus is relatively rapid that this end-tipping, which is merely an exaggerated form of false-bedding, is found. The process can be advantageously studied in the inland lake-basins of New Zealand, North America, and elsewhere.

The Central Sea or Tethys.

This great inland sea is the most striking and important geographical feature of the Mesozoic and Cainozoic, and the sediments laid down on its floor and borders constitute nearly a complete geological history of the Old World in these eras.

This great sea was first outlined during the orogenic movements of the Carboniferous period as a deep corrugation or basin, running east and west in the latitudes of Southern Europe, and lying between the northern and southern continents, into which the Old World at this time became divided.

On the floor of the seas occupying this great corrugation was laid down the Permo-Jurassic succession of conformable strata, so largely represented in the structure of the Alps and Himalayas. But it was not until the Jurassic that the Central Sea formed a continuous sea and completely severed the northern Russo-Siberian continent from the southern or Gondwana-Land continent.

Before the close of the Cretaceous the Central Sea extended from the Atlantic eastward through Southern Europe to Further India and Burma. It girdled half the globe with its length of 9000 miles, and its width varied from 1000 to 2500 miles.

Gondwana Land on the southern shores collapsed sometime about the Middle Cretaceous, perhaps contemporaneously with the great Cenomanian Transgression, and Central and Eastern Africa, a portion of Peninsular India, Malaysia, Australia, and New Zealand are all that now remain to mark its former extent. Of the surface forms of this great continent which covered so large a portion of the present Indian Ocean, or of the outlines of the Central Sea which washed its shores, we have little remaining evidence.

On its north side the Central Sea was deeply indented with bays and great estuaries, into which the rivers draining the more permanent northern continent discharged their loads of detritus.

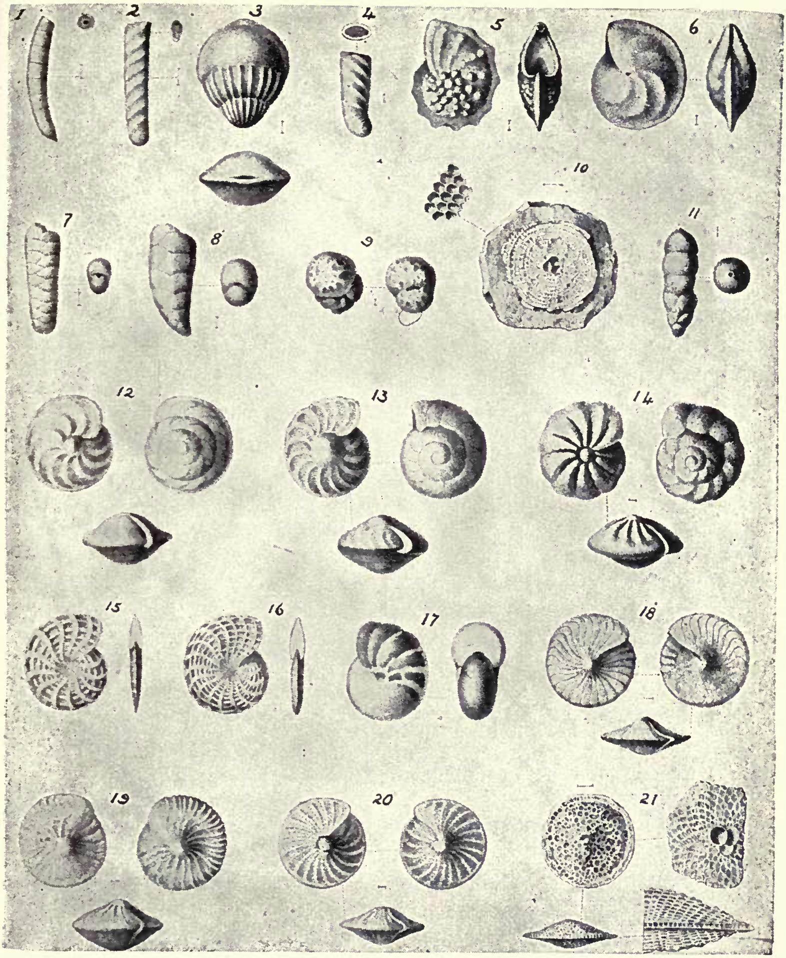
These northern rivers, throughout the Cretaceous, Eocene, and Oligocene periods, reclaimed large deltaic areas on the fringe of the sea. In the clearer waters beyond the reach of the detritus, marine sediments were laid down, largely composed of marine organisms, among which Nummulites predominated. From their nature these marine deposits accumulated more slowly than the deltaic or Flysch detrital sediments, and hence did not attain the same great thickness.

In this manner the Flysch and marine facies of deposits were formed contemporaneously in the same continuous sea, the deltaic as detached but extensive deposits on the northern coasts, the marine as continuous sheets that wrapped round the deltaic and extended seaward into the clear waters.

That the waters of the Central Sea were clear and warm, except in the deltaic areas, up till the close of the Oligocene period is shown by the abundance of reef-building corals, sea-urchins, and the large size of the molluscs and Foraminifera.

The Baltic Sea.—At the close of the Carboniferous there came into existence a northern but smaller sea, running nearly parallel with the Central Sea. This sea followed the Baltic depression, and extended eastward to the Urals; and although varying in width and extent at different periods, it continued an area of deposition up to the close of the Miocene. The Baltic is a remnant of that ancient sea.

Up till the Trias it was separated from the Central Sea by a narrow ridge, but in the Rhætic this separation ceased, and was not renewed until the Cretaceous period. From that time onward the separation continued to be more or less complete, and the dividing chain was broader than at any former time.



FORAMINIFERA. WAITEMATA BEDS, AUCKLAND, NEW ZEALAND LOWER TERTIARY. (After Karrer.)

Fig. 1. *Dentalina æqualis*, Karr.
,, 2. *Vaginulina recta*, Karr.
,, 3. *Lingulina costata*, d'Orb.
,, 4. *Marginulina neglecta*, Karr.
,, 5. *Cristellaria mammilligera*, Karr.
,, 6. *Robulina regina*, Karr.
,, 7. *Textilaria Hayi*, Karr.
,, 8. *Textilaria convexa*, Karr.
,, 9. *Textilaria minima*, Karr.
,, 10. *Orbitulites incertus*, Karr.
,, 11. *Clavulina elegans*, Karr.

Fig. 12. *Rotalia Novo-Zelandica*, Karr.
,, 13. *Rotalia perforata*, Karr.
,, 14. *Rosalina Makayi*, Karr.
,, 15. *Polystomella Fichtelliana*, d'Orb.
,, 16. *Polystomella tenuissima*, Karr.
,, 17. *Nonionina simplex*, Karr.
,, 18. *Amphistegina Campbelli*, Karr.
,, 19. *Amphistegina Aucklandica*, Karr.
,, 20. *Amphistegina ornatissima*, Karr.
,, 21. *Orbitoides Orakeiensis*, Karr.

CHAPTER XXXII.

MIOCENE AND PLIOCENE.

Miocene.

The Miocene Period witnessed great changes in the distribution of land and water in Europe and Asia, including the uplift of the Pyrenees, Alps, Carpathians, and Himalayas.

At the close of the Miocene the main physiographic features of the Old World, as we now know them, were clearly defined. The British Isles and North France, where Miocene deposits are absent, formed dry land; and Germany, which was mostly covered with the sea in the Oligocene Period, now became continental.

In Northern Europe there was widespread uplift, and in Southern Europe the gigantic orogenic movements which folded the Alps and Carpathians were now in progress. The Eocene and Oligocene strata, both marine and deltaic, laid down on the floor and fringe of the Central Sea, became involved in the huge crustal folds of these chains. Moreover, the corrugations, dislocations, and overthrusts which accompanied the crustal movements cut off portions of the sea, that eventually became freshwater lakes.

The North Sea now came into existence, and marine deposits were laid down on its floor in North Germany, in the States of Schleswig-Holstein and Friesland.

Wide arms of the Atlantic filled the basins of the Loire and Garonne, and a long prolongation of the Central Sea spread northward to the Mainz Basin in the Rhine Firth, which at this time drained southward, and thence passed eastwards through Upper Bavaria to the Vienna Basin. Another arm of the Miocene sea stretched round the Carpathians into Moravia, while a greater prolongation spread over South Russia, following a depression, of which the Black Sea and Caspian are the remaining portions.

The Alps and Carpathians were thus completely surrounded by the sea, and stood up as rugged chains near the northern coasts of the Central Sea.

On its south side the Central Sea still overspread large tracts of North-West Africa, and overflowed the maritime lowlands of Spain and Portugal.

The crustal movements which formed the Alps and Carpathians, at the same time raised the floor of the Central Sea in the areas now occupied by Egypt, Syria, Arabia, Asia Minor, and Persia, and uplifted the mountains of Baluchistan and the Himalayas.

This general Miocene uplift broke up the Central Sea, and detached the Mediterranean portion from the Indian Ocean.

The only record of these wide-spread, mountain-building, crustal movements to be seen in England is the monoclinal fold of the Eocene and Oligocene strata on the north side of the Isle of Wight, to which reference has already been made (fig. 73).

In North America the Miocene strata on the Atlantic border and gulf region lie undisturbed, but in the Pacific States they are acutely folded, and in places uplifted to a great height in the Rocky Mountain chain. On the Atlantic side of the continent, there was a slight emergence of the land, as shown by the narrower limits of the Miocene as contrasted with the underlying Eocene.

Fauna and Flora.—The Miocene flora of Europe shows a closer relationship to the existing evergreen floras of India, Australia, and New Zealand than to the existing European deciduous flora. Among the characteristic genera of the Lower Miocene are numerous palms, magnolias, myrtles, laurels, vines, etc., which indicate the prevalence of a warm, subtropical climate. The absence of palms, and the presence of such hardy trees as the oak, elm, beech, etc., in the Upper Miocene, show the advent of cooler conditions in the later half of this period.

The character of the molluscous fauna confirms the evidence of the flora. Among the common genera we have *Murex*, *Ancillaria*, *Cassis*, *Mitra*, *Terebra*, *Arca*, *Mactra*, *Panopæa*, *Pectunculus*, *Tapes*, *Tellina*, *Dosinia*, and other forms that abound in warm seas.

In Spitzbergen, Iceland, Greenland, and North Alaska, the fossil plants are also subtropical, but in Japan, Kamtschatka, Saghalien, and Eastern Siberia the flora indicates a somewhat cooler temperature than the present.

The distinguishing feature of the Miocene fauna is the appearance of the gigantic Proboscidians, *Deinotherium* and *Mastodon*, the last related to the true elephant, which did not appear until later. Among other Miocene mammals are many species of rhinoceros, hippopotamus, and deer; also whales and dolphins.

The Miocene mammalian fauna is prolific and varied, and marked by a conspicuous development of the ungulates and carnivores. The rodents are not so prominent as in the Eocene; and the insectivores and lemuroids show a notable decline.

The marine mollusca show an increasing relationship to existing forms. In Europe and North America frequently a third of the fossil species are living forms.

The zonal distribution of the marine faunas is conspicuous both in North America and Europe. Generally the Northern or Maryland fauna is related to the North European, and the Gulf fauna to the Mediterranean.

Continental Europe.

France.—Deposits of Miocene age are unknown in Britain, but they are typically developed in the district of Touraine, traversed by the rivers Loire, Indre, and Cher. Here they occur in isolated and widely-separated patches of sediments that are mostly marine. They form a sheet which seldom exceeds a thickness of 50 feet, and is locally known as *faluns*, from its fertilising qualities as a dressing for the land.

This deposit contains numerous corals, and over 300 species of molluscs, of which about 25 per cent. are identical with living forms.

The mammals include *Rhinoceros*, *Hippopotamus*, *Chœropotamus*, and *Mastodon*.

Vienna Basin.—This great basin is bounded by the Eastern Alps, the plateau of Bohemia and Moravia, and the Western Carpathians. The group of beds contained in it are divided into three series:—

3. Pontian Series.
2. Sarmatian Series.
1. Mediterranean Series.

This basin began as a salt-water sea and gradually became freshwater.

The deposits of the Mediterranean Series vary considerably in different places. Generally they consist of limestones, clays, marls, and sandstones. The Leithakalk Limestone consists mainly of reef-building corals, bryozoans, and Foraminifera. It also contains numerous sea-urchins, pectens, shark's teeth, and mammalian remains.

The sandstones are mostly freshwater, and with them are associated the brown coals of the Vienna Basin.

Marine molluscs are particularly abundant in this series, and of 1000 species many still survive in the Mediterranean and west coast of Africa.

The flora, like the fauna, possesses a subtropical aspect.

The *Sarmatian* is mainly composed of fresh- and brackish-water sediments, with some intercalating marine beds, from which it would appear that the general uplift of this stage was accompanied by minor oscillations.

Corals, bryozoans, Foraminifera, and sea-urchins, so abundant in the underlying stage, are rare in the Sarmatian, the muddy estuarine conditions being eminently unfavourable for their growth.

Palms are absent among the vegetation of this time, and the Indian forms predominate over the American types.

The *Pontian Series* consists of brackish-water marly clays, with *Unio*, *Congeria*, *Cardium*, *Melanopsis*, etc. It is the division of the Miocene on which Vienna is built.

Switzerland.—The *Swiss Molasse* occupies the whole area between the Alps and the Jura. Near the former it consists of coarse shore-conglomerates, which, with increasing distance seaward, pass into sandy and clayey sediments. The progressive uplift of the Alps continued into the Pliocene, and the conglomerates now lie at a height of 6000 feet, where they exhibit little or no departure from the original horizontal position in which they were deposited.

The *Lower Molasse*, frequently called the *Grey Molasse*, contains numerous plant remains, mainly subtropical, and a marine bed with *Ostrea*, *Venus*, *Murex*, and *Cerithium*. It is succeeded by the true or *St Gallen Molasse*, which contains a rich molluscous fauna comprising some 400 species, of which about one-third are still living.

The St Gallen stage is followed conformably by the *Upper Freshwater Molasse*, with *Melania*, *Unio*, etc., and seams of brown coal.

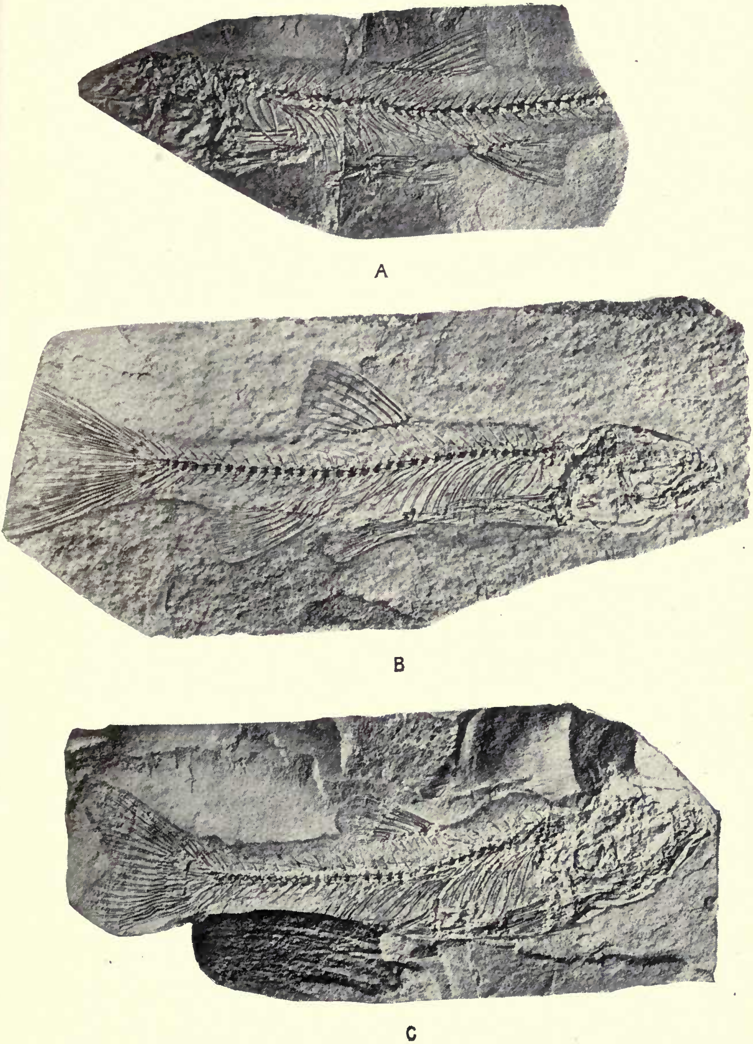
In the Tortonian stage the land surrounding the lake was clothed with a luxuriant vegetation, and peopled with a great assemblage of land animals, which included the tapir, mastodon, rhinoceros, deer, apes, opossums, three-toed horse, squirrels, hares, beavers, and the huge *Deinotherium* which frequented the jungle lands fringing the lake. The waters of the lake teemed with fishes, and the shallow pools and mud-banks were frequented by crocodiles.

The three main subdivisions of the Molasse placed in consecutive order are as follow :—

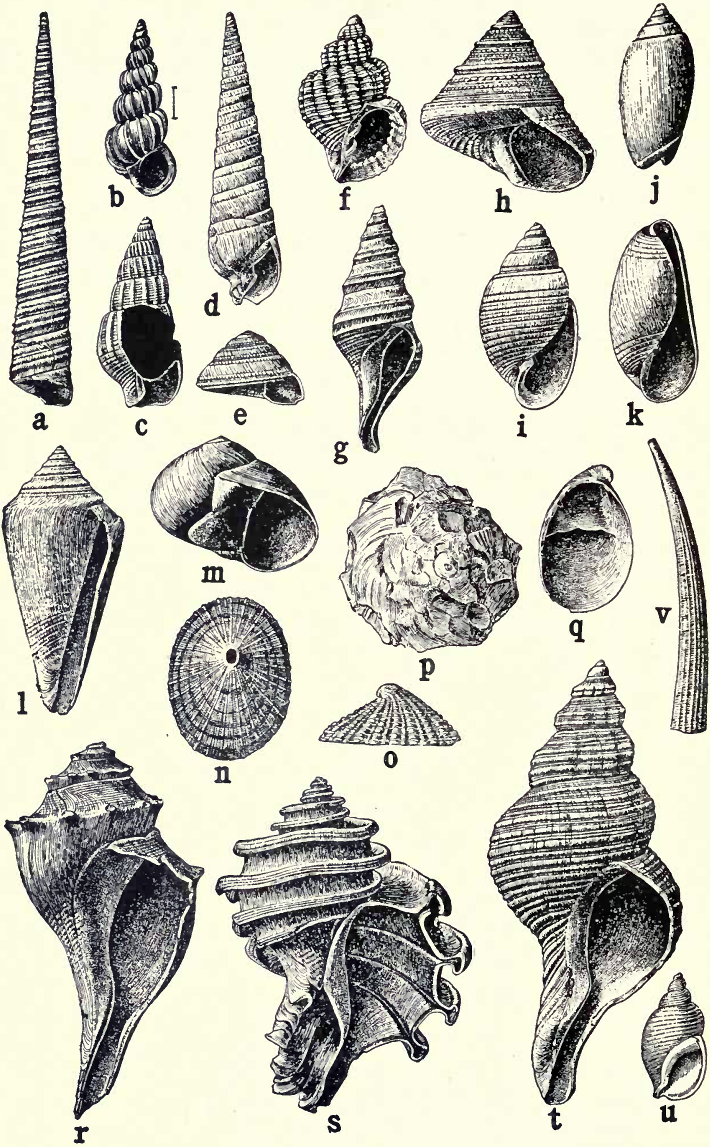
3. Upper Freshwater Molasse—Tortonian.
2. St Gallen Molasse (Marine)—Helvetian.
1. Grey Molasse (Lower Freshwater Stage)—Mayencian.

India.—As previously described in last chapter, the Gaj Series of uppermost Oligocene age is conformably followed by the *Mekran Series* of Older Miocene date, which is well developed along the Mekran coast, in the islands of the Persian Gulf, Irawadi Valley in Burma, and Andaman Islands.

PLATE LIX.



FOSSIL FISH FROM THE ESMERALDA FORMATION, MIOCENE.
(*Leuciscus Turneri*, U.S. Geol. Survey.)



MIOCENE GASTEROPODS.

PLATE LX.

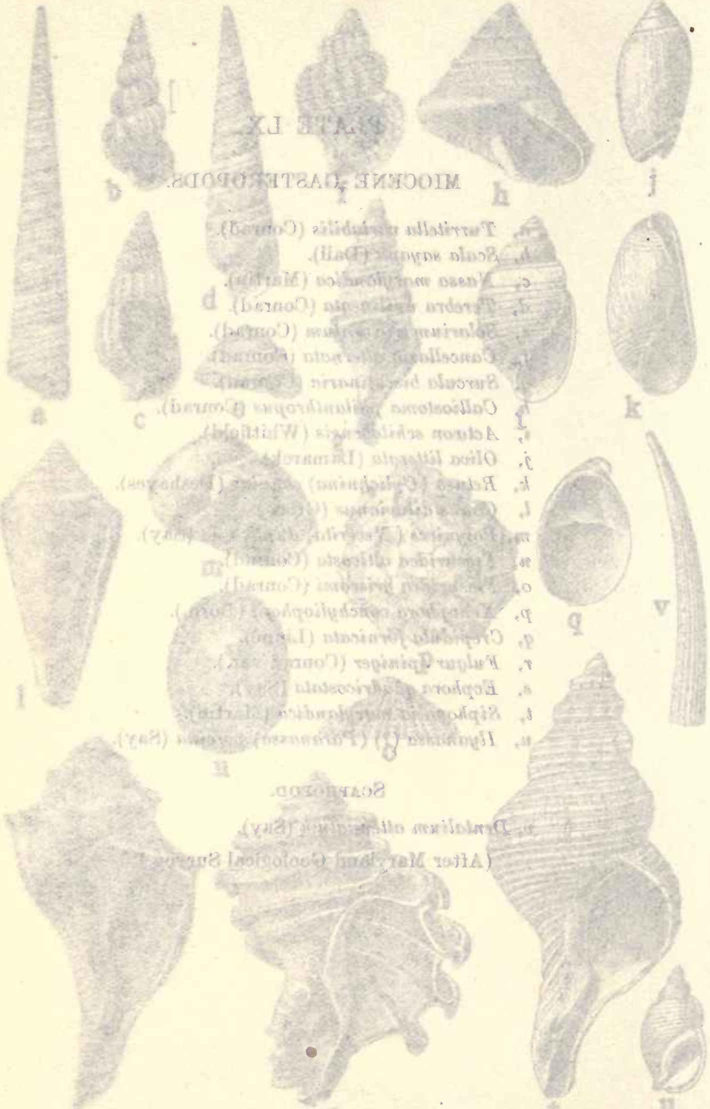
MIOCENE GASTEROPODS.

a, *Turritella variabilis* (Conrad).
b, *Scala sayana* (Dall).
c, *Nassa marylandica* (Martin).
d, *Terebra unilineata* (Conrad).
e, *Solarium trilineatum* (Conrad).
f, *Cancellaria alternata* (Conrad).
g, *Surcula biscatinaria* (Conrad).
h, *Calliostoma philanthropus* (Conrad).
i, *Actæon schilohensis* (Whitfield).
j, *Oliva litterata* (Lamarck).
k, *Retusa* (*Cylichnina*) *conulus* (Deshayes).
l, *Conus diluvianus* (Green).
m, *Polynices* (*Neverita*) *duplicatus* (Say).
n, *Fissuridea alticosta* (Conrad).
o, *Fissuridea griscomi* (Conrad).
p, *Xenophora conchyliophora* (Born.).
q, *Crepidula fornicata* (Linné).
r, *Fulgur spiniger* (Conrad var.).
s, *Ecphora quadricostata* (Say).
t, *Siphonalia marylandica* (Martin).
u, *Ilyanassa* (?) (*Paranassa*) *porcina* (Say).

SCAPHOPOD.

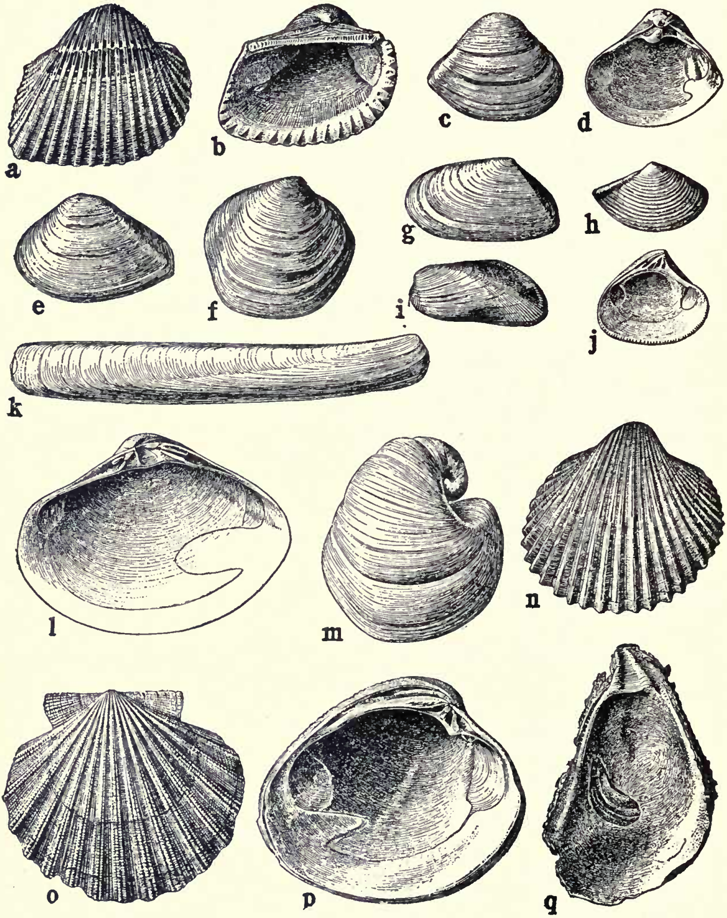
v, *Dentalium attenuatum* (Say).

(After Maryland Geological Survey.)



MIOCENE GASTEROPODS.

[Plate LXI.



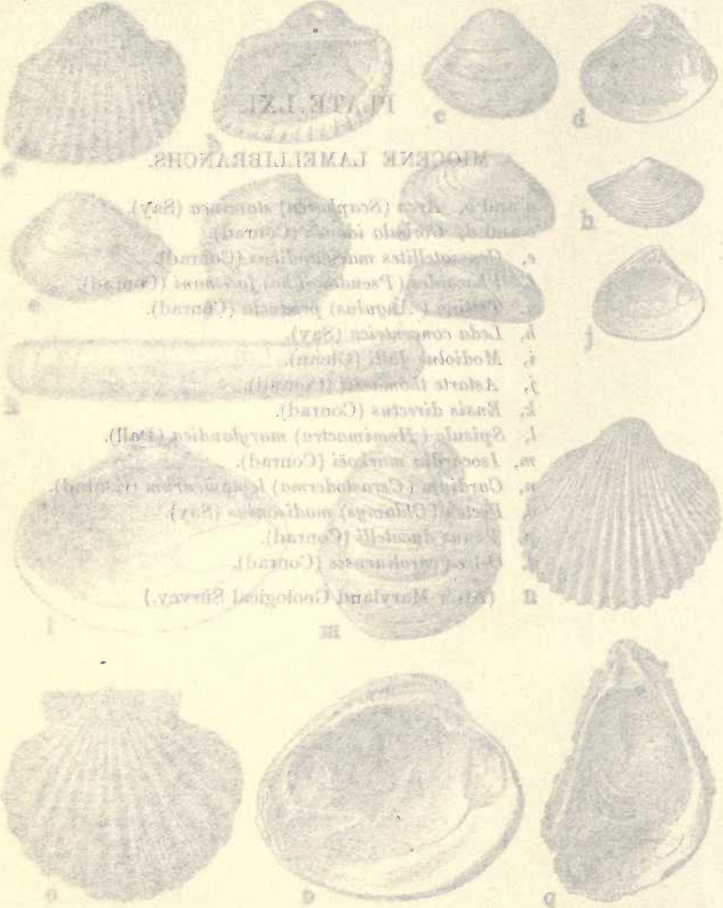
Miocene Lamellibranchs.

PLATE LXI.

MIOCENE LAMELLIBRANCHS.

a and *b*, *Arca* (*Scapharca*) *staminea* (Say).
c and *d*, *Corbula idonea* (Conrad).
e, *Crassatellites marylandicus* (Conrad).
f, *Phacoides* (*Pseudomiltha*) *foremani* (Conrad).
g, *Tellina* (*Angulus*) *producta* (Conrad).
h, *Leda concentrica* (Say).
i, *Modiolus dalli* (Glenn).
j, *Astarte thomassii* (Conrad).
k, *Ensis directus* (Conrad).
l, *Spisula* (*Hemimactra*) *marylandica* (Dall).
m, *Isocardia markoëi* (Conrad).
n, *Cardium* (*Cerastoderma*) *leptopleurum* (Conrad).
o, *Pecten* (*Chlamys*) *madisonius* (Say).
p, *Venus ducatelli* (Conrad).
q, *Ostrea carolinensis* (Conrad).

(After Maryland Geological Survey.)



MIOCENE LAMELLIBRANCHS.

The strata consist of clays, sandstones, and conglomerates of the Flysch facies, intercalated with a few calcareous bands.

The characteristic Foraminifera are *Nummulites* and *Amphistegina.* The uppermost beds contain many large pectens.

Towards the close of the Miocene, the Flysch strata were deeply involved in the great folds which marked the final uplift of the Himalayas. The crustal movement of this date broke up the great Central Sea into disconnected inland seas, and severed the Mediterranean from the Indian Ocean.

The Lower Miocene rocks of India do not possess much economic importance apart from the associated *Pegu* System, which contains valuable oil-bearing strata in Burma and Assam, as well as deposits of salt in the Salt Range in the Punjab.

North America.—The Miocene strata of North America are typically developed on the Atlantic coastal fringe and around the Gulf of Mexico. They dip gently seaward, and in some regions are largely obscured by later accumulations.

In many places along the Atlantic fringe, the Miocene beds appear to rest unconformably on the Eocene (Oligocene), but the stratigraphical break is slight.

Along the Atlantic coast, they are grouped under the name *Chesapeake Series.* For the most part they consist of loose sands, clays, and shelly marls that enclose a rich fauna.

In the Gulf region the Florida Limestone has been largely replaced by rock-phosphate deposits of great extent.

The Miocene of the Pacific Coast, sometimes called the Monterey Series, is restricted to a narrow fringe skirting the coastline; but strata of this age also invade the Central Valley of California.

Generally the Monterey Series of California rests unconformably on the Eocene. It consists mainly of shales, and sandstones with a notable quantity of volcanic ash.

A striking feature is the extraordinary thickness of the shales, 4000 feet, which are largely composed of siliceous diatoms. The thickness of the whole series has been estimated at from 5000 to 7000 feet.

The Miocene System is of great economic importance as one of the oil-bearing formations of California. The older gold-bearing gravels of that State are supposed to be Miocene, and great accumulations of lacustrine deposits occur in the old lake-basins east of the Sierras, and also in Nevada and Montana.

Volcanic activity was conspicuous throughout the whole of the Miocene, and towards the close of the period culminated in gigantic effusions of basaltic lavas. Evidences of volcanic eruptions are abundant in all the Pacific States, in Columbia, and in the Yellowstone National Park, where forests were overwhelmed by ashes, and in favourable situations the tree trunks were silicified.

Altogether during the Middle Tertiary, from 200,000 to 300,000 square miles of the western part of the United States was covered with sheets of basaltic lava.

In the Western States the Miocene was a period of great crustal disturbance; and to this date is assigned the orogenic movements which uplifted the Cordilleran chains, and deformed, partly by folding and partly by faulting, the rocks of the Northern Sierras and Great Basin. In the latter region the crustal movements were accompanied or succeeded by violent volcanic outbursts.

Greenland.—In North Greenland, now covered with polar ice, the plant beds exposed on the coast contain a prolific evergreen subtropical flora. Of 150 species, about half are forest trees, such as the evergreen oak, beech, planes, poplar, maple, walnut, lime, magnolia, and many conifers, including the giant *Sequoia.* A third of the species are found in the Miocene basins of Southern Europe.

In the Miocene of North Greenland, within 8° 15′ of the pole, there occurs a seam of bituminous coal 25 feet thick, embedded in sandstones and shales which contain numerous species of conifers, mostly pines, spruces, firs, and cypresses, and also the Arctic poplar, birch, hazel, and elm. Water-lilies grew on the shallow ponds which were fringed with reeds and sedges.

The Miocene plant beds of Spitzbergen, within 12° of the pole, contain an evergreen vegetation, from which it would appear that the whole of the polar region on this side of the Northern Hemisphere was covered in that period with rank subtropical forests and jungle.

The existence of coal-seams in the Antarctic continent points to similar changes of temperature in the South Polar regions.

The climatic changes which have taken place in past geological times present one of the most difficult problems that confront the geologist.

Australia.—Marine deposits of Miocene or younger date are unknown in Queensland and New South Wales, which, since the Eocene, have remained dry land. In the south-east and southern parts of the continent Miocene beds are extensively developed. In the State of Victoria they cover large tracts, more particularly in Gippsland, where the basal beds of the system contain thick seams of brown coal, one of which at Latrobe shows a thickness of 90 feet.

Miocene beds are sparingly displayed in Tasmania, but at one time they probably covered a considerable area. At Table Cape the deposits contain a rich molluscous fauna as well as the remains of the primitive marsupial *Wynyardia.*

Marine strata of probably Miocene age occur as a fringe on the Great Australian Bight.

Except in Victoria and a corner of Tasmania, practically the whole of Australia was dry land throughout the Miocene and younger Cainozoic. The conditions of deposition were mainly continental; hence the deposits of this period are mostly sands, gravels, and clays deposited in inland basins, or washed into hollows by torrential rains. There was widespread volcanic activity in the Middle Cainozoic, particularly in the eastern side of the continent. Floods of basaltic lavas spread over the country and streamed down the valleys, where they covered up the gold-bearing gravels and other detrital material.

The buried gravels form the famous *deep-leads* of the State of Victoria.

New Zealand.—Miocene strata cover large tracts in both the main islands. The lower beds are terrestrial sands and conglomerates that contain valuable seams of brown coals. They are followed by estuarine clayey and sandy beds. The uppermost beds are marine limestones mainly composed of comminuted corals, bryozoans, and Foraminifera.

Generally the Miocene strata contour around the coasts and ramify into the old firths and valley-basins. They are mostly undisturbed or dip gently towards the sea. In West Nelson they have been raised by a series of powerful parallel faults in step-like blocks to a height of 3500 feet above the sea. In East Nelson they are overthrust and involved in the overturned folds of the Triassic rocks.

The marine beds everywhere contain a rich assemblage of molluscs, among which brachiopods are numerous, also corals, bryozoans, Foraminifera, and sea-urchins. The remains of a zeuglodon whale are common.

On the East Coast of Otago the upper members of the Oamaru Series are intercalated with tuffs and basalt flows.

Antarctic Region.—Tertiary strata occurs at Seymour Island, near Graham's Land, containing a rich molluscous fauna considered by Wilckens to be Upper Oligocene or Lower Miocene.

Pliocene.

At the close of the Miocene there was a general retreat of the sea throughout the whole globe, and in the Pliocene the continents began to assume the definite forms they now possess. It is only in those areas where the Pliocene sea-floor has been uplifted and has escaped complete destruction by denudation that marine deposits of that period are exhibited for our examination. And since upward earth-movements of considerable magnitude have not been general or even widespread in the latest Cainozoic, the amount of dry land now occupied by Pliocene marine strata is relatively small.

The bulk of the Pliocene beds to which we have access are lacustrine and fluviatile deposits of the Continental facies that have accumulated in inland basins and river-valleys. In many places these terrestrial deposits, which are mostly loose, unconsolidated drifts, owe their preservation to a protecting cover of basalt, rhyolite, or other igneous rock.

Of the existing dry land forming Northern Europe, only small areas in East England, Belgium, and North France were covered with the Pliocene sea. Germany, which was mainly dry land in the Miocene, became wholly dry land in the Pliocene; hence marine beds of Pliocene age are not represented among the rock-formation of that region.

In Southern Europe, around the Mediterranean Basin, the sea encroached on the maritime borders of Spain, Algeria, and Greece, and covered large tracts in Sicily, Central and South Italy.

In North America there was the same general recession of the sea as in Europe; and since the sea-floor has not been uplifted to any extent since the Pliocene, marine strata of that date are but poorly represented on this continent, and occur only as a narrow interrupted fringe bordering the Atlantic and Gulf coasts. On the other hand, detrital deposits of the Continental facies are well developed in the old lake-basins, and along the Atlantic and Gulf maritime borders.

A general recession of the sea took place in India, Australia, South Africa, and South America, and it is only where uplift has taken place that Pliocene strata are exposed at the surface.

The Pliocene was a period of notable volcanic activity in Western North America, India, Australia, and New Zealand.

Fauna and Flora.—Most of the molluscs and other invertebrates of the Pliocene fauna are recent species; but of the vertebrates, almost all the species and even many of the genera are extinct.

Where the Cainozoic succession is complete, the Pliocene follows the Miocene conformably, and is conformably followed by the Pleistocene. The limits of these systems are quite artificial, and the faunas show a progressive organic development when passing upwards from one system to the other.

Perhaps the most notable feature of the Pliocene land fauna is the presence of the large extinct Proboscidians *Deinotherium*,[1] and *Mastodon*.[2] Other mammals are very abundant, and include

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[1] Gr. *deinos* = terrible, and *therion* = an animal.

[2] Gr. *mastos* = nipple, and *odous* = tooth.

many species of rhinoceros, deer, antelopes, giraffes, ox, cat, bear, fox, porcupine, beaver, and various apes. The true elephant, *Elephas meridionalis*, appears about the close of the period.

The Equidæ are represented by the existing horse, *Equus*, and by the horse-like *Hippotherium gracile* with three toes on each foot, only the central toe reaching the ground.

The marine fauna of Southern Europe closely approaches that of the living Mediterranean fauna, and in North-West Europe that of the boreal seas. At the same time many Arctic species appear in the Pliocene deposits of both Italy and England.

Foraminifera, corals, and bryozoans are exceedingly abundant, and the molluscous fauna is very prolific, particularly in Lamellibranchs and Gasteropods, of which about 90 per cent. are still living.

British Isles.—The only important Pliocene deposits in England occur as a coastal strip in East Anglia, where they are well exposed in the sea-cliffs and beaches from Walton in Essex to Weybourn, north-west of Cromer in Norfolk. A few small patches survive on the Downs of East Kent, and a small deposit occurs at St Erth in Cornwall.

Seven subdivisions of the Pliocene are recognised in England, but there is no general agreement as to how the deposits of this period should be divided :—

- Newer Pliocene
    - 7. Cromer Forest Bed Series.
    - 6. Weymouth Crag.
    - 5. Chillesford Clays.
    - 4. Norwich Crag.
    - 3. Red Crag.
- Older Pliocene
    - 2. Coralline Crag.
    - 1. Lenham Beds.

The different subdivisions are seldom found superimposed on one another; but proceeding northwards along the coast from Walton we pass successively from older to younger beds. From this it would appear that the deposits were laid down on the littoral of a sea, slowly retreating northwards.

The fauna of the Older Pliocene is essentially that of a warm sea, and of the Newer Pliocene of boreal waters.

The molluscous fauna of the older Pliocene comprises a large proportion of southern forms. But the uplift which caused the northward retreat of the sea cut off communication with the southern sea about the Red Crag Stage. The entrapped southern forms were unable to survive in the colder waters of the North Sea; and at the close of the Red Crag Stage half of them had disappeared, while an increasing number of northern forms took their place.

The influx of northern forms and corresponding disappearance of the southern were accelerated by the gradual approach of the Arctic cold, which culminated in the Pleistocene.

As the polar ice crept southward, more and more of the southern forms succumbed to the increasing cold, and at the close of the Norwich Crag, there was not a survivor left. Thereafter, only northern forms inhabited the North Sea.

The land flora of the Newer Pliocene was less affected by the increasing cold than the more delicately organised marine fauna, and at the close of the period still possessed the aspect of a temperate climate.

The *Lenham Beds* occur as a number of small patches on the North Downs between Maidstone and Folkestone at heights ranging from 500 to 600 feet above the sea. They contain some species found in the Miocene, among them being *Pleurotoma Jounanetti*, *Terebra acuminata*, and *Arca diluvii*.

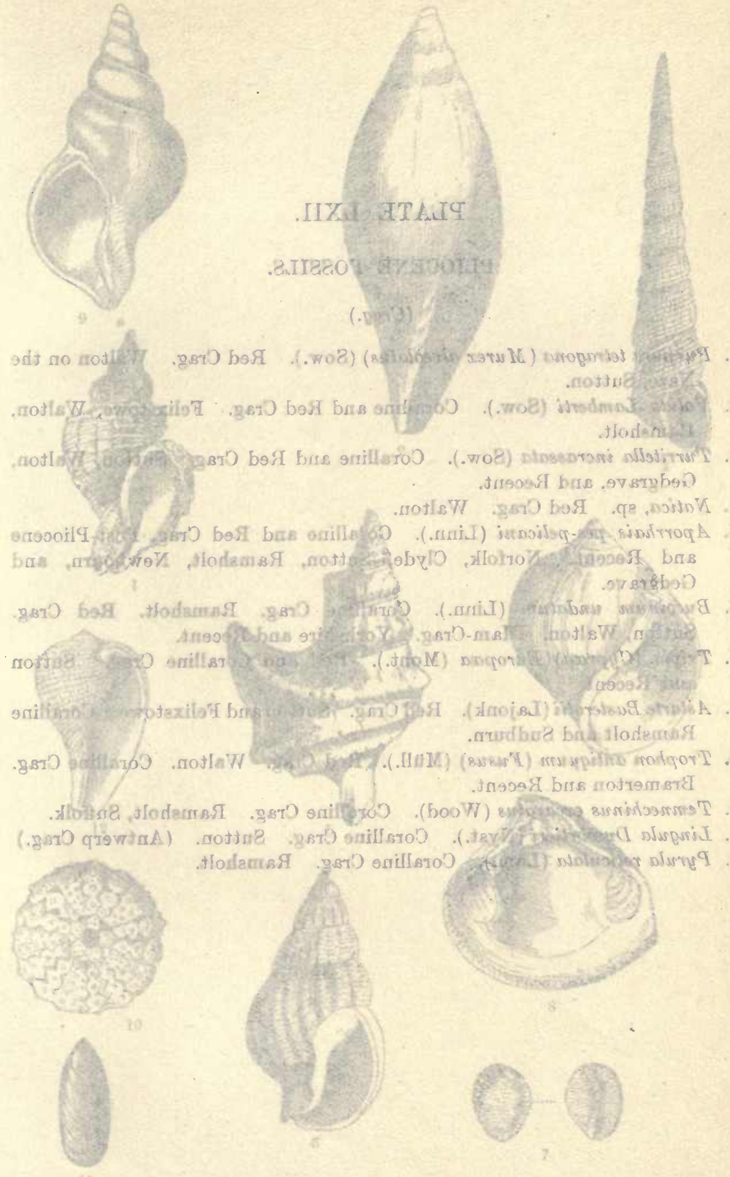
The *Coralline Crag* is only known in South-East Suffolk, where it is well exposed in the neighbourhood of Aldeburgh and Orford. It consists mainly of fragments of polyzoans, molluscs, sea-urchins, and fish teeth, and may be regarded as a raised shell-bank. At its base, at Sutton, there is a phosphatic nodule bed with fossils derived from the London Clay and Jurassic rocks. This bed also contains an assortment of different rocks, such as flints, granite, quartzite, quartz, sandstones, etc. The rounded blocks of brown sandstone are locally called *box-stones*.

The *Red Crag* consists of sands frequently current-bedded, and shells usually broken. The sands and shells are stained a reddish-brown colour with peroxide of iron, hence the name *Red Crag*. Among the southern forms in this bed are *Cerithium trilineatum*, *Nassa limata*, and *Turritella incrassata* (Plate LXII. fig. 3), and among the northern, *Natica occlusa*, *Pleurotoma pyramidalis*, *Cardium grœnlandicum*, *Astarte Basterotii* (Plate LXII. fig. 8), and *A. borealis* (Plate LXV. fig. 3).

The *Norwich Crag* is a shelly sand and gravel deposit of fluvio-marine origin. A considerable proportion of the shells are fresh-water. This stage is specially noted for the large number of mammalian bones which occur in a pebbly bed at its base. The mammals include representatives of the horse, mastodon, and elephant.

Among the characteristic boreal molluscs are *Astarte borealis* and *Nucula Cobboldiæ* (Plate LXV. fig. 4).

The *Chillesford Beds* in different places rest on the Norwich, Red, and Coralline Crags. They consist mainly of finely laminated



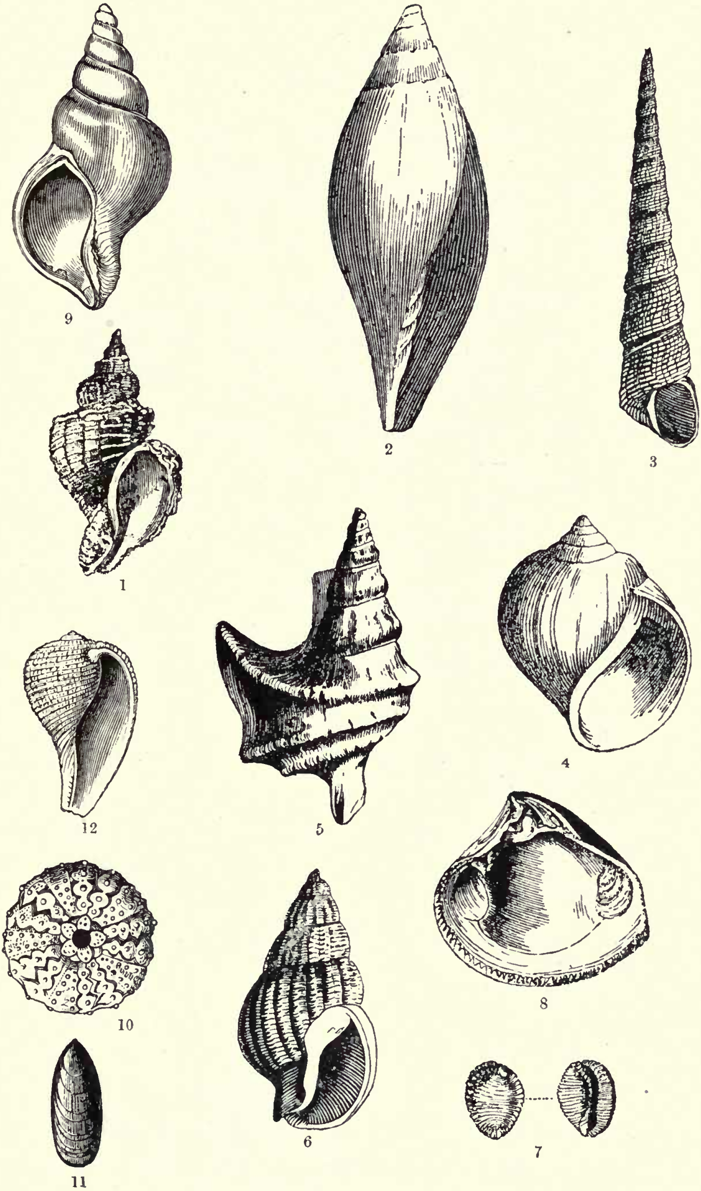
PLIOCENE FOSSILS. *(Crag.)*

PLATE LXII.

PLIOCENE FOSSILS.

(*Crag.*)

1. *Purpura tetragona* (*Murex alveolatus*) (Sow.). Red Crag. Walton on the Naze, Sutton.
2. *Voluta Lamberti* (Sow.). Coralline and Red Crag. Felixstowe, Walton, Ramsholt.
3. *Turritella incrassata* (Sow.). Coralline and Red Crag. Sutton, Walton, Gedgrave, and Recent.
4. *Natica*, sp. Red Crag. Walton.
5. *Aporrhais pes-pelicani* (Linn.). Coralline and Red Crag, Post-Pliocene and Recent. Norfolk, Clyde, Sutton, Ramsholt, Newbourn, and Gedgrave.
6. *Buccinum undatum* (Linn.). Coralline Crag. Ramsholt. Red Crag. Sutton, Walton. Mam-Crag. Yorkshire and Recent.
7. *Trivia* (*Cypræa*) *Europæa* (Mont.). Red and Coralline Crag. Sutton and Recent.
8. *Astarte Basterotii* (Lajonk). Red Crag. Sutton and Felixstowe. Coralline Ramsholt and Sudburn.
9. *Trophon antiquum* (*Fusus*) (Müll.). Red Crag. Walton. Coralline Crag. Bramerton and Recent.
10. *Temnechinus excavatus* (Wood). Coralline Crag. Ramsholt, Suffolk.
11. *Lingula Dumortieri* (Nyst.). Coralline Crag. Sutton. (Antwerp Crag.)
12. *Pyrula reticulata* (Lam.). Coralline Crag. Ramsholt.



Pliocene Fossils. (*Crag.*)

micaceous clays and sands. Among the numerous species of molluscs are *Astarte compressa, Cardium grœnlandicum, Lucina borealis,* and *Cyprina islandica.*

The *Weybourn Crag* is a marine shelly deposit which contains most of the molluscs of the Chillesford Clays, and also the Lamellibranch *Tellina balthica,* which is unknown in older beds.

The *Cromer Forest Bed Series* is well developed in the Cromer Cliffs on the north coast of Norfolk. It comprises four distinct groups of beds:—

Cromer Forest Bed Series
4. *Leda* (*Yoldia*) *myalis* Bed (marine).
3. Upper Freshwater Bed.
2. Forest Bed (estuarine).
1. Lower Freshwater Bed.

The plant beds contain the remains of many forest trees, almost all of which are still living in Norfolk. All the marine molluscs are found in the Weybourn Crag. They include the extinct species *Tellina obliqua* and *Nucula Cobboldiœ.*

The vertebrates are exceedingly abundant and comprise numerous fishes (perch, cod, pike, sturgeon, etc.), reptiles, and birds (eagle, owl, cormorant, wild goose, wild duck, etc.). The marine mammals include whales, seals, and walrus. The ungulates are represented by the elephant, rhinoceros, hippopotamus, horse, bison, and wild boar; and the carnivores, by the hyæna, wolf, dog, fox, otter, and marten.

Excluding the bat, the total species of land mammals is forty-five, as compared with twenty-nine living species. And of thirty large land mammals only three are now living in Britain, and only six survive elsewhere.

The *Leda myalis* Bed is a current-bedded, sandy, marine loam containing a few marine shells of boreal aspect, among which *Leda myalis, Tellina balthica,* and *Astarte borealis* are common.

The *Arctic Freshwater* Bed which follows the *Leda myalis* Bed conformably is sometimes referred to the Pliocene and sometimes to the Pleistocene. It contains the Arctic willow, *Salix polaris,* and the Arctic birch, *Betula nana,* which indicate a mean temperature 20° Fahr. lower than the present mean temperature, sufficiently cold to allow glaciers to form on the mountains, and allow the sea to be frozen over in the winter months.

Belgium.—The Pliocene deposits across the Channel are a continuation of those in the east coast of England. The Older Pliocene deposits consist of shelly sands, and rest unconformably on the Miocene and older rocks. The fossils are mostly those which characterise the Coralline Crag and older Pliocene of England.

France.—In South France the Pliocene deposits have been raised to a height of 1150 feet above the sea. They consist chiefly of shelly sands and marly clays with bands of conglomerate. The three main divisions are as follow :—

3. Arnusian Stage—Freshwater, with volcanic tuffs.
2. Astian ,, Fluviatile, lacustrine, and marine.
1. Plaisancian ,, Marine.

Italy.—The Pliocene of Italy and Sicily are more fully developed than elsewhere in Europe. They occupy large tracts in Central and Southern Italy, forming low hills on both flanks of the Apennines; hence the name *Sub-Apennine Series* frequently applied to the Italian Pliocene.

In Sicily they cover about half the area of the island, and rise to a height of 4000 feet above the sea. The volcanic activity which piled up Etna to its present gigantic size began in the Pliocene, the first eruptions being submarine. Since then the island and surrounding sea-floor have been steadily rising. The marine benches that contour round the north and east sides of the island are conclusive evidence of uplift in quite recent times.

The fauna is rich in molluscs and mammals, most of them related to forms found in the Pliocene of England.

Vienna Basin.—The Pliocene beds of this basin follow the Miocene quite conformably. They are usually called the *Congerian Stage* from the abundance of the Lamellibranch *Congeria subglobosa.* The deposits consist of clays followed by fluviatile drifts.

The clays are estuarine and contain a rich assemblage of molluscs and mammalian remains. The overlying fluviatile drifts also contain mammalian remains.

The *Congerian Stage* was apparently deposited in a gulf that became detached from the sea, forming an inland basin like the present Caspian depression ; and, like the Caspian Sea, it gradually freshened by the inflow of streams and rivers.

In the arms of the sea cut off from the great Central Sea, there accumulated remarkable deposits of rock-salt, gypsum, and anhydride, the most famous of which is that at Wieliczka in Polish Austria, on the northern flank of the Carpathians, near Cracow.

India.—The uplift of the Himalayas and the mountains of Baluchistan and Burma culminated in the late Miocene, consequently there are no marine Pliocene deposits in these regions. But along the foot of the Himalayas there remained a chain of salt-water basins and shallow lagoons, in which a thick series of deposits was laid down during the Pliocene Period. These beds consist principally of fluviatile sands, clays, and conglomerates, and constitute what is widely known as the *Siwalik System*, which is extensively developed in the Punjab, Baluchistan, Burma, and Assam. In Burma the Siwalik System is represented by the *Irawadi Beds.*

The sediments of this system were deposited by the streams and rivers flowing into the enclosed basins, their mode of formation in some respects resembling that of the *Flysch* deposits.

The variable salinity of the waters of these detached basins was unfavourable for the development of a prolific or vigorous organic life, the remains of which are consequently scanty. The molluscs are mostly living species; but the chief interest of the Siwalik System lies in the extraordinary number of fossil vertebrates which it contains. The mammals include many apes, the elephant and mastodon, numerous ungulates and carnivores. Fishes, reptiles, and birds are also well represented.

The living mammals include the elephant, horse, and bear.

North America.—Marine Pliocene beds play an unimportant part in the geological structure of the North American continent. They are sparingly developed along the Atlantic and Gulf coasts, occurring as isolated patches that are probably the remnants of a continuous sheet. The strata dip seaward under the accumulations of later date.

The bulk of the Pliocene deposits are lacustrine and fluviatile drifts that have accumulated in inland lake-basins.

The *Lafayette Series*, which consists of a series of sands, clays, and silts, is extensively developed between the Appalachians and the Atlantic, whence it sweeps around the Atlantic border to the Mexican Gulf coastal region. It spreads over a large tract in the lower Mississippi Basin and stretches into the coastal plains of Texas. Altogether this series covers an area exceeding 200,000 square miles.

The beds rest unconformably on the eroded surfaces of the Miocene and older rocks, and seldom rise to a height exceeding 200 feet above the sea.

The thickness of the sediments seldom exceeds 50 feet, and is usually less than 30 feet, but in a few places it reaches 200 feet.

This remarkable and widespread maritime formation contains no marine fossils, and the remains of land animals and plants are rare. Hence its age is still uncertain. Although obviously of terrestrial origin, its mode of formation is still obscure.

Australia.—The gold-bearing drifts of Victoria and New South Wales that lie buried under sheets of basaltic lava range in age from Miocene to Pliocene. These buried *deep-leads* frequently contain lignite beds, and the trunks, branches, and leaves of trees, also freshwater shells and the remains of extinct marsupials, some of which attained a gigantic size. The most remarkable of these primitive mammals are the *Diprotodon*, the tapir-like *Nototherium*, a giant kangaroo, a marsupial lion, and a marsupial hyæna.

The Pliocene drifts also contain the remains of a large extinct bird, *Dromornis*, related to the existing emu.

Marine beds of Tertiary date occur in the State of Victoria up to an altitude of 1000 feet above sea-level. The fossils include the brachiopod *Magellania*, the Lamellibranch *Trigonia*, and the Gasteropods *Haliotis* and *Cerithium*.

New Zealand.—Marine deposits of Pliocene age cover a wide tract in the North Island, where they rise as a gentle sloping plane from sea-level to a height of 4000 feet above the sea. They rest conformably on the Miocene strata, but overlap these and spread on to older rocks. Their uplift, like that of the Pliocene of Sicily, was connected with volcanic outbursts which piled up the gigantic volcanoes Ruapehu and Tongariro, both situated in the centre of a great dome of elevation, from which the Tertiary strata dip towards the sea on the west, south, and east.

The molluscous fauna is related to that in the surrounding seas.

Some of the older gold-bearing drifts of Otago and Westland are probably Pliocene.

CHAPTER XXXIII.

PLEISTOCENE AND RECENT.[1]

Pleistocene or Glacial Period.

THIS period covers the interval between the close of the Pliocene and the advent of recent times. Its downward limit is not always very sharply defined from the Pliocene, and passing upward it merges imperceptibly into the Recent.

The duration of this period has been variously estimated at from scores of thousands to hundreds of thousands of years, which is a good reason for saying that we possess no sufficient data to enable us to form even an approximate estimate. Whatever its length expressed in years may be, it is generally agreed that the Pleistocene represents a shorter interval of geological time than the Pliocene or other Cainozoic periods.

The time that has elapsed since the close of the Glacial Period is estimated at from 10,000 to 50,000 years.

During the Pliocene, the Alps, Carpathians, Himalayas, and other great chains attained their full height, and at the close of that period the Earth finally assumed its present form. Since that date there have been no great earth-movements except those caused by local volcanic disturbances, but, as in past ages, the various processes of denudation have been unceasingly wearing away and modifying the surface of the dry land.

Pleistocene Glaciation.—The dominant feature of this period was the phenomenal increase of cold in both hemispheres, which permitted an extraordinary invasion of the temperate latitudes by gigantic ice-sheets moving down from the higher latitudes, and allowed glaciers to accumulate in regions where permanent ice did not formerly exist.

A vast ice-sheet radiated from the mountains of Scandinavia and spread over the whole of Northern Europe. It extended from the Ural Mountains to the Atlantic Ocean, and reached as far south as Central Germany and the basins of the rivers draining

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[1] Pleistocene + Recent = Post-Pliocene = Quaternary, when the geological record was divided into Primary, Secondary, Tertiary, and Quaternary eras.

into the Black Sea. This gigantic sheet bridged the Baltic Sea and filled the North Sea basin, in which it flowed southward as far as the English Channel. Its southmost limit in Europe was about 50° N. latitude.

At the same time enormous glaciers radiated from the Pyrenees, Alps, Carpathians, Urals, and Caucasus, and spread over the foothills and neighbouring plains.

The whole of Scotland and practically the whole of Ireland were covered with ice, and in England the invading sheet reached as far as the basin of the Thames.

The magnitude of the Pleistocene glaciation was even greater in North America than in Europe. Glacial drifts were spread over the United States as far south as 37° N. latitude, or 13° further south than in Europe.

In South America and New Zealand the glaciers reached sea-level in 39° S. latitude, and in the Antarctic Continent the extent of the Barrier Ice-sheet was vastly greater than at present.

The trend of the later researches in glaciology is to show that Europe and America were not glaciated by an invasion of the polar ice-cap, but by the accumulation of vast masses of ice in certain regions situated in lower latitudes. In Europe the centre of dispersion is placed in Northern Scandinavia; and in North America, in Canada along the sixtieth parallel of latitude. The evidences of regional glaciation are not sufficiently conclusive for general acceptance, and, after all, may be deceptive; and perhaps too much weight has been attached to the apparent absence of glaciation in Southern Siberia, and to the radial dispersion of the Scandinavian ice-sheet.

At each independent local centre of glaciation the ice-cap will naturally flow outward in all directions from the gathering ground independently of the surface configuration. In the case of valley glaciers the direction of flow will always be determined by the trend of the valley-walls.

In Scotland the local ice-cap radiated north, east, south, and west. It flowed north and east until it became engulfed in the superior mass of the southward-flowing Scandinavian ice-sheet.

Similarly the Scandinavian land-ice radiated outward towards all the cardinal points of the compass, and there is no evidence to show that it did not meet and merge into the advancing polar ice-sheet.

The great glaciation of North and North-West Europe may have been directly due to the existence of the superior gathering ground in Scandinavia. But there is no present evidence to show that the existence of the Scandinavian ice-sheet was independent of an advance of the polar ice-cap.

In North America the Pleistocene ice-cap covered Greenland and the whole of the northern portion of the continent, with perhaps the exception of North-West Alaska, as to which the evidence is too scanty for final pronouncement. The centres of accumulation and dispersion of the land-ice were localised in certain regions from which the confluent ice-sheets radiated in all directions, but there is no evidence to support the view that these accumulations of ice could have existed apart from a general refrigeration and advance of the polar ice-sheet.

The extreme cold which characterised the older Pleistocene did not come on suddenly. On the contrary, the effects of boreal cold began to be manifest as far back as the Middle Pliocene. The wholesale migration of Arctic forms into the East Anglian waters in the Newer Pliocene showed that the Scandinavian region was already in the grip of the ice-cap, and the advent of the boreal flora as contained in the Arctic Freshwater Bed denoted that the refrigeration was approaching a climax. After this stage, the cold continued to increase until the glaciation culminated about the Middle Pleistocene.

Subdivisions.—It is maintained by some eminent geologists that there were two periods of glaciation separated by a warmer interval, during which the ice-sheets and glaciers retreated. This warmer interval is called the *Interglacial Period.* Its supposed existence is based on the occurrence of certain drifts with plant and peaty deposits and mammalian remains intercalated in the Boulder-Clay. A better knowledge of the work of glaciers and ice-sheets does not support this view.

It is almost certain that the advance and retreat of the northern ice was sufficiently slow to permit forests to flourish and peat-bogs to accumulate on the drift-covered lands close to the edge of the ice. During a temporary advance of the ice, the forests might well be covered over by fluvio-glacial sands, gravels, and morainic débris.

Three principal stages of glaciation may be distinguished in the Glacial Period, and they pass imperceptibly into one another. They are the *Advancing Stage*, the *Maximum Stage*, and the *Retreating Stage.*

The Ice Age in temperate latitudes began and ended in local glaciers which became confluent during the maximum refrigeration.

The *Advancing Stage* is characterised by the gathering of local glaciers—the outposts of the advancing northern ice. The *Maximum Stage* is distinguished by ice-sheets of great magnitude, and the *Retreating Stage* by local glaciers that cover the retreat of the main sheet and finally disappear or shrink back among the deep mountain valleys. Thus we have :—

Glacial Period
3. Retreating Stage = Local glaciers.
2. Maximum Stage = Confluent glaciers and ice-sheets.
1. Advancing Stage = Local glaciers.

In the *Advancing Stage* the glaciers that already existed in the Alpine chains began to advance and grow in thickness. At the same time the seasonal snows on the lower ranges became permanent, and glaciers appeared where none existed before. A wintry boreal aspect now took possession of the land, and the Arctic plants and animals slowly retreated southward before the advancing ice, always keeping within the limits of climatic conditions corresponding to their natural habitat.

With the increasing refrigeration, the glaciers grew in size until they filled up the valleys and basins in which they lay.

In the *Maximum Stage* the advancing glaciers overflowed the valley-walls and deployed on to the foothills and plains, where they formed piedmont ice-sheets that slowly crept onwards until in some cases their terminal face was hundreds of miles from the centre of dispersion. In their onward course they passed over hill and dale, filled up lake-basins, and even bridged wide seas. In this stage the ice-sheets derived little or no rocky débris from projecting peaks or *nunataks*; nevertheless, they carried an immense load of soil, clay, sand, and broken rock scooped up from the floor over which they flowed. The conditions now resembled those prevailing in Greenland at the present time.

In the *Retreating* or *Waning Stage*, as the result of the gradual approach of milder climatic conditions, the ice-sheets began to shrink and retreat, and in time they disappeared from the coastal plains and foothills. Shrunken in thickness and no longer able to override the valley-walls, the ice now began its long retreat up the mountain valleys.

When half-way back to the Alpine chain, the glaciers in the temperate regions halted and entrenched themselves behind piles of morainic débris. Behind these temporary fortresses they held their ground for a time, and on two or more occasions made desperate sallies beyond the barriers. Beaten back by the increasing and relentless warmth, they soon began the final retreat which ended in the disappearance of all but those which took their rise in the higher Alpine chains.

Glacial Evidences.—Glaciers and ice-sheets leave behind them a twofold evidence of their former existence. By their erosive effects, they modify the configuration of the surfaces over which they pass, and they leave behind them piles of detrital material of various kinds.

A glacier or moving sheet of ice by the sheer weight of its mass removes all the irregularities of the surfaces over which it flows, with the result that the contours become rounded and smooth. Rough rocky hills lying in the path of the moving ice are worn down into rounded, hummocky, or whale-backed mounds or *roches moutonnées*, and the surfaces of the rocks are scored, scratched, and polished by the cutting effect of the blocks embedded in the bottom of the ice. Protruding spurs are truncated, and benches, steps, and broad platforms frequently excavated on the mountain slopes. Prominent peaks and ridges that are overridden by a stream of ice are worn down into rounded domes.

A region that has suffered intense glaciation usually presents smooth flowing contours and soft outlines.

The detrital material consists mainly of fluvio-glacial drifts, terminal morainic piles often arranged in crescent-shaped mounds, and ground-moraines called *till* or *boulder-clay*.

Fluvio-Glacial Drifts.—Glaciers and ice-sheets in all the stages of their existence are drained by streams and rivers which pick up and re-sort the detritus discharged at the terminal edge, and spread it out as a wide sheet or apron of rudely-sorted, water-worn, and semi-angular drift in front of the ice-sheet. In this way glacial valley-trains are formed (fig. 29).

Older Drifts.—The drifts formed during the advancing stage are obviously the oldest. In many places they were cut up by the advancing ice, carried forward, and again deposited at the terminal face.

It is obvious that, where the ice-stream travelled far from its gathering ground, the drifts and detritus laid down in the earlier stages of the advance may have been re-sorted over and over again before the ice-flow reached its furthest limit. The constituent particles and blocks by the continuous grinding and attrition of the moving ice and the wear and tear of the glacial streams and rivers become smaller and more rounded. Hence, in a long journey only the harder rocks are able to survive in the form of sand and gravel. The softer rocks are reduced to the condition of silts and muds, much of which is carried to the sea by the glacial streams.

Morainic Mounds.—These are formed at the halting-places both during the advance and retreat. The morainic mounds formed during the advance are overrun by the ice when it resumes its forward movement, and are thereby broken up and re-deposited in a re-sorted form. The morainic mounds formed during the retreat remain intact except where they have been attacked by the glacial streams and rivers issuing from the ice-face.

Terminal moraines are formed at the utmost limits reached by the ice, provided the retreat does not begin as soon as this limit is reached.

Older Moraines.—When the ice-sheet halted for a time at the utmost limits reached by it, the rocky load of débris transported under, in, and on the ice is piled up as a terminal moraine. Such moraines are of great antiquity, and are obviously older than those formed during the retreat. Hence they are called *Older Moraines* to distinguish them from the *Newer Moraines* formed in the valleys and old alpine lake-basins during the later stages of valley glaciation.

Boulder-Clays or *Ground-Moraines.*—During the retreat the rocky débris entangled in the ice is shed as a sheet over the ground from which the ice has disappeared. In places the deposit may be thick, in others thin or altogether absent according to the distribution of the material in the ice. It may be spread over valley, hill-top, and slope alike, but is usually thickest in the hollows, as the tendency of the newly fallen material is to gravitate downwards.

At certain places the ground-moraine may be attacked and re-sorted by the glacial streams issuing from the ice, and spread out as an apron of drift and silt in front of the terminal edge. In this way a boulder-clay may pass gradually, or may be suddenly, into rudely stratified sand and gravel drifts.

There is abundant evidence that a boreal vegetation and land animals followed up the retreating Pleistocene ice pretty closely, and in this situation their remains would be liable to be covered over with glacial débris during minor advances of the ice arising from fluctuations in the climatic conditions.

Thickness of Ice-Sheets.—The thickness of the Scottish ice-sheet during the period of maximum refrigeration as determined by the height at which ice-worn rocks are met with has been estimated at 5000 feet; of the Scandinavian, 7000 feet; of the New Zealand, 7000 feet; and of the North American, from 7000 to 15,000 feet.

Local Glaciation.

British Isles.—During the period of maximum glaciation the whole of Scotland was covered with a sheet of land-ice which radiated outwards from the Highlands in all directions. On the east side the Scottish ice spread some distance over the sea and repelled the invading Scandinavian ice which now occupied the North Sea, and on the west it covered all the Western Isles and stretched an unknown distance into the Atlantic. The portion covering the Western Lowlands crossed the Irish Sea and invaded the north-east corner of Ireland.

Passing southward it encountered the Welsh buttress with its ice-cap, and was diverted into two main streams, the eastern stream flowing southward through the Lancashire depression between the Pennine Chain and Highlands of Wales, the western or main stream pursuing its course down the Irish Sea between South-East Ireland and Wales.

The Irish Sea was so completely filled that the ice rode over the summit of Snaefell, the highest point in the Isle of Man, which is 2034 feet above the sea.

The Lancashire ice-stream flowed as far south as the basin of the Severn, and covered the greater portion of Lancashire, Cheshire, and Shropshire.

The western stream passed through St George's Channel, chafed against the rocky coasts of Pembroke, and advanced so far south that the ice-face peeped into the Bristol Channel.

The local glaciers of Ireland formed a sheet of land-ice which covered the whole of the island, with the exception of Counties Antrim and Down, and some adjacent areas in the north-east corner already occupied by the Scottish ice, and perhaps a fringe along the south coast.

The Welsh glaciers formed a small but compact wedge of ice lying between the two main branches of the Scottish ice. On the west side they descended into Cardigan Bay, and fended off the Scottish ice; on the south sent long tongues of ice into the Bristol Channel; and on the east descended into the basin of the Severn.

The Scandinavian ice filled the North Sea and reached as far south as the English Channel, but it was unable to encroach on the Scottish mainland on account of the superior pressure of the land-ice descending from the Highlands.

In England, where the land-ice was thinner and its pressure less, the Scandinavian ice was able to invade the coastal fringe from North Durham to the Humber. South of the Humber it spread over a large tract, covering practically the whole of Lincolnshire lying east of the Trent, the whole of the counties of Norfolk, Stafford, and Cambridge, and portions of the adjoining Midlands, as far south as the north side of the Thames Valley.

Local glaciers held possession of the Cheviot Hills on the border, and the highlands of Cumberland and Westmoreland.

The former extent of the local glaciers and invading Scottish and Scandinavian ice is shown by the distribution of the rocky débris and erratics scattered over the land, and by the direction of the ice-striated rock-surfaces.

The main struggle for supremacy between the Scottish and Scandinavian ice-sheets seems to have centred about the north-east corner of England, and partly as a result of this struggle, and partly as the result of the check the Scottish ice received from the Cheviot barrier, and the resistance of Northumberland and Westmoreland glaciers, there appears to have remained a neutral ground—a kind of no-man's-land—embracing a large portion of the North, East, and West Ridings of Yorkshire, and the greater part of Nottinghamshire lying west of the Trent, where no ice intruded.

Glacial Deposits.—The character of the glacial deposits varies from place to place, and is largely dependent on the character of the rocks and the local conditions of glaciation.

Generally the glacial deposits of a region may be classified as (*a*) those formed during the Advancing Stage; (*b*) those that accumulated at the utmost limits reached by the ice; and (*c*) those formed during the Retreating Stage.

The pre-glacial deposits are mainly fluvio-glacial drifts, and from their nature are mostly composed of local detritus.

The deposits formed during the maximum refrigeration are mainly terminal moraines which may contain erratics mingled with the local débris, and widespreading aprons and trains of fluvio-glacial drift formed by the streams issuing from the ice-face.

The glacial deposits of the Retreating Stage are mainly boulder-clays intercalated with fluvio-glacial drifts. It is in this stage that *eskers* of sand and drift are formed in subglacial channels and ice-tunnels.

There is no general agreement as to the succession of the different glacial deposits scattered throughout the British Isles, and much diversity of opinion exists as to how some of them were formed. And the difficulty is complicated by the presence of organic remains in some of the deposits. But perhaps this difficulty is not so great as it appears. The ancient belief that the advance of the northern ice necessarily involved the destruction of all animal and plant life in its neighbourhood is now known to be fallacious. Recent research has shown that forests may flourish and peat-bogs grow on the moraines and valley-trains of a glacier up to the edge of the ice. Forests may even establish themselves on the clays and rocky débris carried on the back of a glacier.

In New Zealand there is the instructive spectacle of the famous Franz Josef Glacier embowered in a luxurious evergreen forest at a height of 670 feet above the sea, in 43° S. latitude.

It is certain that where forests could grow, the woolly mammoth and woolly rhinoceros, the Arctic reindeer, the moose, and bear would find a genial habitat.

Forests and peat-bogs in front of a glacier are always liable to be covered over by fluvio-glacial drifts or overwhelmed by ice during a temporary advance of the ice.

The rapid advance of the Malaspina Glacier, in Alaska, which followed the great earthquakes at Yakutat Bay in 1899, caused a wholesale destruction of the forests lying in front of the ice-face.

The *till* or Boulder-Clay of Scotland is spread over the lowlands and mountain valleys, and usually rests on ice-worn rocks. It consists mainly of stiff, unstratified clay mingled with semi-angular blocks of stone, and varies from 0 to 100 feet thick.

In some places near the coast the till overlies beds containing Arctic shells, and in other places it is intercalated with sand, gravel, laminated clay, and layers of peaty material with plant remains, and the teeth and bones of the mammoth and reindeer.

The Boulder-Clay of England is well developed in East Anglia and the countries around the Wash, where four local subdivisions are recognised :—

4. The Chalky Boulder-Clay.
3. Mid-glacial Drift.
2. The Contorted Drift.
1. Cromer Till.

The *Cromer Till* consists mainly of stiff glacial clays with striated fragments of chalk, flint, and an assortment of Jurassic rocks, Carboniferous limestones, and various igneous and metamorphic rocks. Some of the boulders are clearly erratics from the north. The rhomb-porphyry is believed to have come from the neighbourhood of Christiania, and also the boulders of the rock called *Laurvikite.*

The *Contorted Drift*, which is well exposed in the Cromer Cliffs on the north coast of Norfolk, is a yellowish-brown loam, with irregular layers of gravel, sand, and clay. It contains many boulders and some enormous blocks of chalk. This deposit is rudely stratified, and on the north coast sharply contorted, a feature resulting probably from ice-thrust.

The *Mid-glacial Sands* contain marine shells and ostracod crustaceans of a northern type.

The *Chalky Boulder-Clay* rests on the Contorted Drift, but also extends far beyond the limits of that deposit, being found as far south as the Thames Basin. Generally it does not differ much from the Cromer Till, but contains fewer Scandinavian boulders.

The Chalky Boulder-Clay is so named from the prevailing colour and the presence of numerous fragments and blocks of chalk. It passes north of the Wash into Lincolnshire and East Yorkshire. The infra-glacial beds at Speeton contain land and marine shells and the remains of mammals, among them being *Elephas antiquus*, *Rhinoceros*, and *Hippopotamus*.

In East Anglia Scandinavian blocks are comparatively common, in East Yorkshire they are rare, and further north in Scotland they are practically unknown, the pressure of the Scottish land-ice having thrust the Scandinavian North Sea ice away from the mainland.

Most of the erratics in the Boulder-Clay of England are from Scotland and North England. For the most part they are igneous rocks of limited outcrop and distinctive character, and hence easily traced to their original source.

The Scottish ice flowing down the Irish Sea transported blocks of the riebeckite-granite from its source at Ailsa Craig, on the Firth of Clyde, to the Isle of Man, Anglesey, and St David's Head in Pembrokeshire.

Among other erratics carried southward are the grey granites of Galloway, the pink granophyre and granites of the Lake District, and the andesites of the Borrowdale Volcanic Series. Boulders of the famous Shap granite were carried from the Lake District eastward into Yorkshire by way of Teesdale.

In Lancashire, Cheshire, and north coast of Wales, the Boulder-Clay is irregularly intercalated with shelly sands and gravels that do not occur in a constant horizon.

At Macclesfield, in Cheshire, these shelly deposits occur at a height of 1200 feet above the sea, and are held by some writers to be a proof of submergence. The shells, however, are often striated, and comprise a mixture of deep and shallow water forms, and though embedded in clay they are frequently filled with sand. The shells are always associated with erratics transported across an arm of the sea, and were doubtless scooped up from the sea-floor and transported in the body of the ice to their present situations.

Vast numbers of shells, mostly unbroken, were discovered by Lamplugh in the terminal moraine of the Sefström Glacier, Spitzbergen, after it had crossed an arm of the sea. This occurrence is of great significance. It is corroborated by similar evidence from Alaska; and shows how readily marine material can be lifted from the sea-floor and transported by an advancing sheet of land-ice.

The Lancashire branch of the Scottish ice-sheet from the Irish Sea reaches as far south as Wolverhampton, in South Staffordshire, where it dropped a vast number of erratic boulders. The southern limits of the ice-sheet in the Thames Basin are not marked by a terminal moraine, which would indicate that the ice did not halt when it reached these limits, but began the northerly retreat almost at once, scattering an irregular sheet of boulder-clay in its wake.

The city of York is built on the terminal moraine of one of the tongues of ice that protruded from the Scottish ice-sheet.

Continental Europe.

The Scandinavian ice-sheet passed over Finland and spread into North-East Russia, reaching as far as the Ural Mountains. It bridged the Baltic Sea, advanced southward across the great Germanic Plain, and even reached the northern slopes of the Harz Mountains and Riesengebirge, where it scattered Scandinavian erratics of gneiss, granite, etc., up to a height of almost 1500 feet above the sea.

The maximum thickness of this gigantic ice-sheet is estimated to have been not less than 7000 feet.

The glacial detritus scattered over Northern Europe varies from 0 to 670 feet thick, and generally decreases in thickness from north to south.

The deposits exhibit many local variations, which frequently take place with startling suddenness. But as in other glaciated regions, the succession is difficult to unravel.

The lowest deposits are fluvio-glacial drifts composed of well-worn sands and gravels formed by the streams and rivers that issued from the front of the advancing ice-sheet. These *Pre-glacial Drifts*, as they are sometimes called, are followed by boulder-clays, which consist of stiff clays, with numerous blocks of stone only slightly rounded and frequently scratched, grooved, and polished. The lower portion of these glacial clays is a bluish-grey colour which weathers to a yellowish-brown near the surface. Furthermore, as in England and Scotland, the boulder-clays are intercalated with irregular deposits of fluvio-glacial drift composed of sand, gravel, and silt, often rudely stratified. In these so-called *Inter-glacial Drifts* are found the teeth and bones of mammals, peaty matter, and plant remains. Among the mammals are the mammoth, rhinoceros, giant elk, reindeer, ox, bear, etc., which are common in the neighbourhood of Berlin.

These animals probably followed the retreating ice-sheet, and frequented the broad reed and moss-covered plains spread out in front of the ice. There they lived and died in great numbers. When the ice-sheet made minor advances, the drift with their remains became covered over with a sheet of boulder-clay.

Along the Baltic fringe the glacial clays contain many marine molluscs, among which *Leda* (*Yoldia*) *arctica*, *Cyprina islandica*, and *Corbula gibba* are prominent.

The northern glaciation was accompanied by a great extension of the Alpine glaciers, and glaciers occupied the slopes and deep valleys of the Pyrenees, Vosges, Black Forest, Harz, Riesengebirge, Urals, and Caucasus, where permanent ice-fields no longer exist.

The Pleistocene was a period of great fluviatile activity. Fluvio-glacial and fluviatile drifts were spread over the valley-floors to a great depth, far in advance of the limits reached by the ice, forming high-level flood-plains.

These drifts were deposited during both the advance and retreat of the ice, and hence range in age from the earliest to the latest Pleistocene. The rivers, in the process of excavating their present channels, have in many places left strips or remnants of these drifts at different levels along the valley-walls. Obviously the lowest terraces are composed of the oldest drifts, and the highest terraces of the youngest.

The *loess*, which covers a large portion of Northern Europe, and extends from the English Channel to Galicia, Hungary, and Russia, is probably the wind-borne flood-silt of the rivers draining the front of the ice-sheet, mingled with wind-blown desert-dust. It spreads over hill and dale, and varies from 0 to 80 feet thick.

The loess is an excessively fine, yellowish, powdery, unbedded loam, and is frequently calcareous. When exposed in natural cliffs or artificial cuttings, it shows a tendency to assume a vertical cleavage.

Among the land shells found in this remarkable silt are *Helix hispida*, *Succinea oblonga*, and *Pupa muscorum*, which are characteristic and widely spread. The remains of the mammoth and rhinoceros are not uncommon.

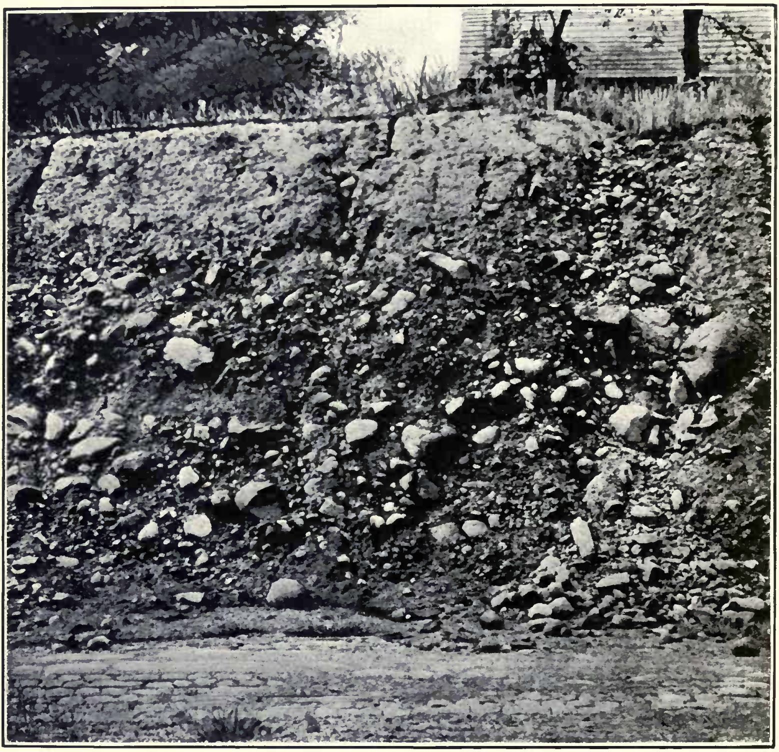
Northern Asia.—Of the Pleistocene glaciation of this region very little is known. It is, however, quite certain that the glaciers of the Himalayas extended far beyond their present limits, but how far has not yet been ascertained.

The great piles of morainic material in the valley of the Kotchurla River show that the ancient glaciers of the Altai Mountains at one time spread northwards many hundreds of miles from their gathering ground. A few small glaciers still cling to the mountain slopes at the sources of the Mushtuaire River in the Obi Basin. Some of the valley-glaciers in alpine Turkestan are of gigantic size.

The taigas and tundras of Northern Siberia are covered with a vast sheet of fluvio-glacial drift, and as in Northern Europe and North America, the mammoth occupied a prominent place in the fossil fauna.

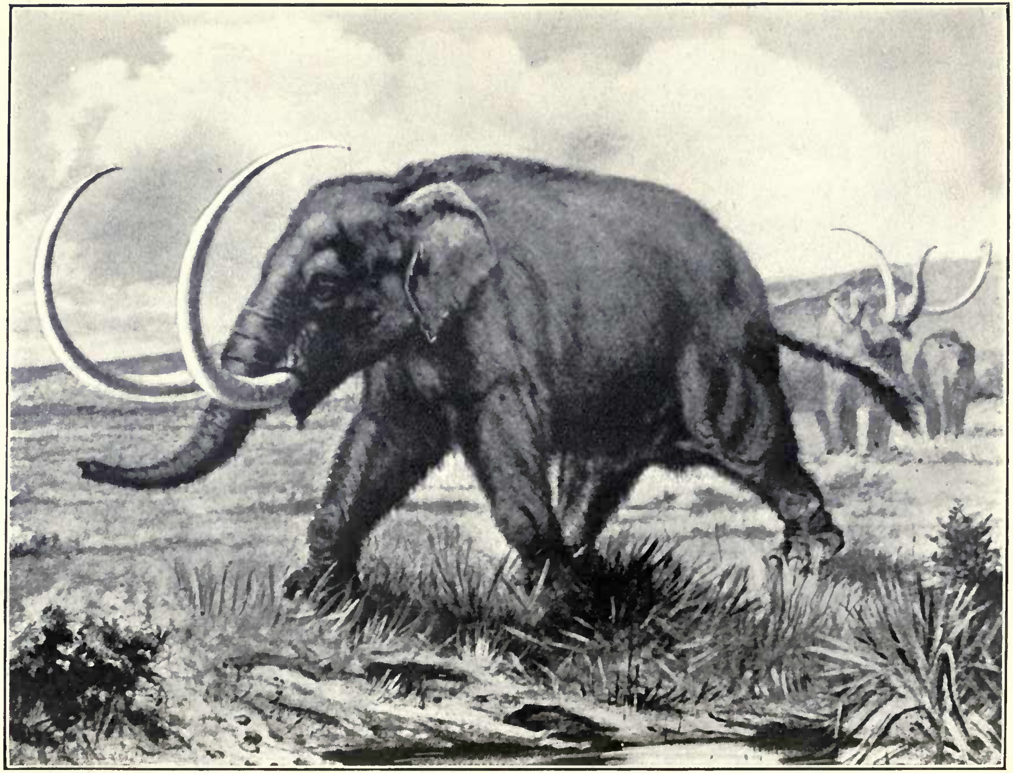
The mammoth lived in extraordinary numbers along the northern border of that region, where the well-preserved bodies are found in the permanently frozen soil.

The constant companion of the mammoth, and like it protected with a coat of woolly hair, is the boreal rhinoceros (*Rhinoceros antiquitatis*). With these also occur the bones of the horse (*Equus fossilis*) and *Hippopotamus major*, the last scarcely distinguishable from the living *H. amphibius*.



SECTION OF GLACIAL DRIFT. NORTH-EAST PART OF NEWARK, NEW JERSEY. (N.J. Geol. Survey.)

To face page 473.] [Plate LXIV.



Painted by G. M. Gleeson.]

Mastodon Americanus. (After Chamberlin and Salisbury.)

North America.—The Pleistocene glaciation of this continent was even greater and more intense than in Northern Europe.

There is evidence that the northern half of the continent from the Atlantic to the Pacific was covered with a continuous ice-sheet, which stretched northward toward the polar regions and spread southward into relatively low latitudes.

The confluent ice-sheets are believed to have radiated from four main gathering grounds, namely, the Greenlandian, Labradorian, Keewatin, and Cordilleran, the last three situated on the mainland between the parallels 52° and 55° N. latitude. The Labradorian centre lay about 1800 miles east of the Keewatin or Central gathering ground, and the Cordilleran about 1000 miles west of the Keewatin. The ice-streams from these centres, though so far apart, united as they radiated outward into a gigantic sheet, which altogether covered an area of about 4,000,000 square miles.

The Cordilleran or Western ice-sheet crept southward to 47° N. latitude, and the Labradorian to 37° or 1600 miles from the centre of dispersion. From the great glacial centres the confluent ice-sheets spread northward, and probably joined the advancing polar ice.

The glacial drifts spread over the land by the Pleistocene ice-sheet vary from 0 to 500 feet thick, and erratics have been found over 1000 miles away from the parent rock in the north.

The mammalian remains in the glacial drifts include the mammoth and mastodon (Plate LXIV.), but the rhinoceros, hippopotamus, and hyæna, so common in the drifts of Northern Europe, are absent in North America.

Fluvio-glacial drifts are conspicuous in the Western States, particularly in the Great Basin lying between the Rocky Mountains and Sierra Nevada Chain. In this region there exists several large lake-basins that have been partially or completely filled by glacial drifts. The most notable of these glacial lakes are Lake Bonneville, of which the Great Salt Lake is the remnant, and Lake Lahontan. The drifts in the former are mingled with a considerable quantity of volcanic ash, the product of eruptions within the lake area.

Southern Hemisphere.

The evidences of intense and widespread glaciation are plentiful in South America, Falkland Islands, New Zealand, New South Wales, Tasmania, and Antarctic Continent.

In 1872 Agassiz,[1] the veteran glaciologist, announced the discovery of evidence that South America in the Pleistocene Period was covered with a continuous ice-sheet extending from

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[1] A. Agassiz, *Am. Jour. Sc.*, 1872, vol. iv. p. 135.

the Atlantic to the Pacific as far north as 37° S. latitude, or 1400 miles north of Cape Horn. But long prior to this, Darwin had called attention to the thick masses of boulder-clay and other criteria of glaciation in Tierra del Fuego.

The Pleistocene fauna of South America is distinguished from that of North America by the presence of gigantic sloths and armadillos, which were indigenous to that region.

The advance of the southern ice was accompanied by a corresponding development of Alpine glaciers in the Central Andes. In Bolivia glacial deposits cover both sides of the Andes, and are particularly well displayed along the western slopes, where they are piled up on the foothills to a depth of many thousand feet. In many places the streams draining the existing glaciers have excavated profound gorges through these accumulations. At La Paz the glacial drifts are intercalated with thick deposits of volcanic tuff and breccia. Obviously the Pleistocene glaciers of this region attained gigantic proportions.

In **New South Wales** Mount Kosciusko was covered with a cap of glacier-ice, and in Tasmania glaciers of considerable magnitude descended almost to sea-level.

Owing to its isolation Australia followed its own lines of development. The vertebrate fauna still consists exclusively of marsupials and monotremes, the last represented by the singular *Ornithorhynchus* provided with a duck bill and webbed feet.

In **New Zealand**, with its massive Alpine Chain as a gathering ground, the confluent glaciers descended to the sea-coast all round the South Island, and covered the greater portion of the surface with an almost continuous ice-sheet, through which only the higher peaks projected as gigantic *nunataks*.

In this region, where the evidences of intense and prolonged glaciation are remarkably well preserved, there is nothing to indicate more than one period of Pleistocene refrigeration, which, as in Europe, may be divided into three phases or stages, each characterised by its peculiar glacial accumulations.

In the *Advancing Stage* the glaciers descended the valleys and filled up the great lake-basins lying at the foot of the Alpine Chain with fluvio-glacial drifts. The pre-glacial drifts were afterwards cut up and deeply eroded by the advancing glaciers, which continued their seaward journey until they emerged on the foothills and coastal plains.

On the west coast the confluent glaciers extended far out to sea ; but on the east coast they halted at the present coast-line, where the confluent glaciers formed a piedmont ice-sheet, on the terminal front of which there were piled up vast morainic accumulations. Of these the Taireri Moraine in East Otago is perhaps the largest


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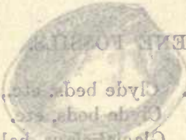


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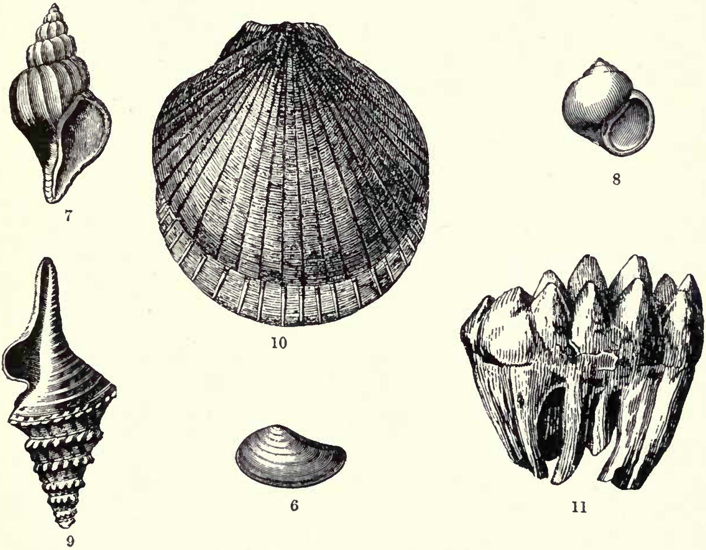
POST-PLIOCENE FOSSILS.

PLATE LXV.

POST-PLIOCENE FOSSILS.

1. *Pecten islandicus* (Müll.). Clyde beds, etc., reduced.
2. *Saxicava rugosa* (Penn.). Clyde beds, etc.
3. *Astarte borealis* (Chem.). Glacial clays, half natural size
4. *Nucula Cobboldiæ* (Sow.). Glacial and Mam. Crag.
5. *Tellina proxima* (F. & H.) *lata* (Gmelin).
6. *Leda oblonga* (Sow.) (*lanceolata*). Glacial beds and Arctic seas.
7. *Trophon clathratum* (Linn.). Glacial beds.
8. *Natica clausa* (Brod.). Glacial beds.
9. *Pleurotoma rotata* (Def.). (Murex Brocc. Sub-Apennines.)
10. *Pecten pleuronectes ?*
11. Tooth of *Mastodon*, one-fourth natural size.

To face page 474.] [PLATE LXV.



POST-PLIOCENE FOSSILS.

in existence. It is 35 miles long, and varies from a few hundred yards to three miles wide, forming a coastal range of hills which rises in places to a height of over 1000 feet above the sea.

The great Marlborough Moraine, which occurs 300 miles further north, can be traced along the east coast for 30 miles up to latitude 41° 30′ S.

In the North Island of New Zealand the existing Ruapehu glacier sent long streams of ice down the neighbouring valleys.

When the glaciers in their retreat had reached the inland basins sheltered by the coastal ranges, they halted and for a time entrenched themselves behind barriers of morainic material which they piled up to a great height. On two occasions they made minor advances of ten or twelve miles, and then began the final retreat which ended in the extermination of all but the larger glaciers, the remains of which still occupy the Alpine Chain.

During the retreat vast quantities of fluvio-glacial drift were shot into the inland basins, most of which were completely filled up. At the present day the filling up of the remaining lakes is proceeding with almost incredible rapidity.

The **Antarctic Continent** is covered with a vast polar ice-sheet from which gigantic glaciers descend to the sea all around the continent.

In **South Victoria Land** the confluent glaciers descend to sea-level and form the famous Ross piedmont ice-sheet which stretches northwards across the deep sea for hundreds of miles, its outer edge forming the well-known Great Ice Barrier first seen by Ross.

The gigantic glaciers, the phenomenal Ice Barrier, the ice-worn domes, and scattered erratics found on both sides of the continent, are sufficient to warrant the view expressed by Scott and others that the Antarctic glaciation of the Pleistocene must have been vastly greater than at present.

During the Glacial Period the Scandinavian ice-sheet extended across the North Sea many hundreds of miles, and the Antarctic ice-sheet still extends over the sea for 500 or 700 miles, notwithstanding that the maximum glaciation is now long past.

How far the ice extended northward during the Glacial Period is unknown. It seems not improbable that the ice-sheet from Graham's Land crossed the intervening sea to the Falkland Islands and met the land-ice which spread over the southern portion of South America. The ability of land-ice to spread over deep seas, so long denied, is now generally recognised by geologists.

Causes of Glacial Period.—Many hypotheses have been advanced to account for the Pleistocene refrigeration, but as yet no agreement has been arrived at, and the final solution seems as far off as ever.

Among the more probable causes that have been suggested we have :—

(1) Variations in the eccentricity of the Earth's orbit, as advanced by Croll.
(2) Wandering of the polar axis.
(3) Depletion of the carbonic acid in the atmosphere first suggested by Herbert Spencer and afterwards urged by Arrhenius.
(4) Climatic changes arising from Pliocene uplift of great chains.

It is now realised that powerful climatic changes may be caused by the elevation of land masses such as great mountain-chains, and that these meteorological changes may be accentuated by a redistribution of land and sea, causing a deflection of established sea-currents.

The present trend of investigation is to lay less stress on probable astronomical causes, and to devote more attention to the analysis of the effects of land-masses, air- and sea-currents, variations of precipitation, etc.

It is suggestive that the great mountain-building of the Carboniferous was followed by widespread glaciation in the Permian Period in both hemispheres.

Recent, Post-Glacial, or Human Period.

The end of the Pleistocene or Glacial Period is not very clearly defined, but is usually placed at the time when the ice-sheets retreated from the lowlands in temperate latitudes.

The Glacial Period can only be regarded as a past geological age in the latitudes from which ice-sheets have completely disappeared. Greenland is still in the Ice Age. The climatic conditions which now exist in that northern land are not unlike those prevailing in Northern and Central Europe during the period of greatest Pleistocene glaciation. Similarly the Antarctic region has passed the ice-cap stage and is now in the waning stage, characterised by gigantic valley-glaciers and piedmont ice-sheets.

Deposits.—The deposits of the Recent Period include those now in process of formation, such as river silts, sands, and gravels; beach sands, muds, and gravels; desert sands, dust, and soils; growing peat-bogs; the detritus from recent volcanic eruptions; the shell-banks and coral reefs growing on the sea-coasts. They also comprise those lately formed, such as river flats, old fluviatile fans, peat-bogs, cave-deposits, sand-dunes, and raised beaches. The growth of formation of some sand-dunes, peat-bogs, and fans has been continuous from the close of the Pleistocene up till now.

Since the beginning of the Human Period, the streams and rivers have cut their channels a few feet or few yards deeper, and the sea has encroached on the land, or the land on the sea; but these changes are relatively insignificant.

Fauna and Flora.—The existing fauna and flora are more prolific and varied than at any other period of the Earth's history.

Foraminifera, which first appeared in the Cambrian, now attain their greatest development. Nummulites, which were so numerous and large in the Eocene and Oligocene, are now represented by one or two rare species found in subtropical waters.

The single corals, which were almost unknown until the early Cainozoic, are exceedingly numerous; and rock-building corals, which have played an important *rôle* as geological agents since the remotest times, still thrive as abundantly as ever in the warm clear waters of the tropical seas, and, as in former ages, are accompanied by sea-urchins and starfishes in great numbers.

Crinoids, which attained their greatest development in the Silurian Period, are now rare.

Brachiopods, which dominated the marine faunas of some of the Palæozoic formations, have shown a steady but slow decline since the Silurian, and at the present day are represented by a mere handful of genera, among which we still have *Rhynchonella*, *Terebratula*, *Magellania*, *Crania*, *Discina*, and *Lingula*. The first and last three are forms of great antiquity. Although only a few genera survive, the individuals of some species exist in such vast numbers as to indicate a great reserve of latent vitality.

Molluscs are represented by hordes of Lamellibranchs, Gasteropods, and Cephalopods, the geographical distribution of which is now more than ever dependent on climatic conditions and environment.

The Cephalopods, with chambered shells so numerous in the Jurassic and Cretaceous periods, are poorly represented in the Cainozoic era. But we still have the *Nautilus*, the fragile Argonaut, and the beautiful *Spirula*, which is sometimes cast up on sandy shores in thousands.

Cephalopods of the octopus and cuttle-fish kind are more plentiful than ever, the only fossil form of these of any importance being *Belemnites*, of which there were scores of species in the Upper Mesozoic.

Crustaceans are still represented by a vast number of Ostracods, Cirripedes (barnacles, etc.), and Isopods (lobsters, cray-fish, crabs).

Fishes, birds, reptiles, and mammals now attain their greatest development.

The dominating figure among the mammals is man (*Homo sapiens*); hence the name *Age of Man*, sometimes applied to the Recent Period.

In the Australian Continent, on account of its isolation and persistence as a land-surface, the marsupial mammals and the primitive Eucalyptus vegetation still dominate the fauna and flora.

The plant remains discovered in Middle Cainozoic rocks in Greenland, Alaska, and Antarctic regions, supplemented by the abundant evidence provided in temperate and tropical countries, shows that nearly all plant families, except such specialised forms as the *Orchidaceæ* among the Monocotyledons, and the *Compositæ* and their allies among Dicotyledons, were at one time more widely distributed than at present.

Subdivisions.—The remains of man and traces of his handiwork have been found in drifts ascribed to the Pliocene Period, but the evidence has been challenged, and in every case the age of the deposits is open to doubt.

Human remains or weapons are seldom found except in drifts that are clearly of Post-Glacial age; but the presence of these would tend to show that man already existed in Southern Europe in the Glacial Period, and followed the ice as it retreated northward.

There are no unquestioned evidences of man in the glacial deposits of England; and since the land connection between Britain and the Continent was probably not broken until the late Pleistocene, it seems unlikely that he would venture into this region until the ice-sheet had disappeared for some time from the lowlands. It is almost certain that man would follow and not precede the vegetation and land-animals which followed close on the wake of the retreating ice.

The remains of man that mostly occur are the weapons and implements he fashioned and used; and as these show a progressive development of skill in their manufacture the nearer we approach our own time, they afford a means of dividing the Human Period into stages. The earliest weapons and implements were made of stone and bone; hence the earliest Human Period is called the *Stone Age*, which was successively followed by the *Bronze Age* and *Iron Age*.

(3) Iron Age.
(2) Bronze Age.
(1) Stone Age $\left\{\begin{array}{l}\text{(b) Neolithic.}\\\text{(a) Palæolithic (Plate LXVI.).}\end{array}\right.$

In the *Palæolithic*[1] or *Old Stone Age* the weapons, tools, etc.,

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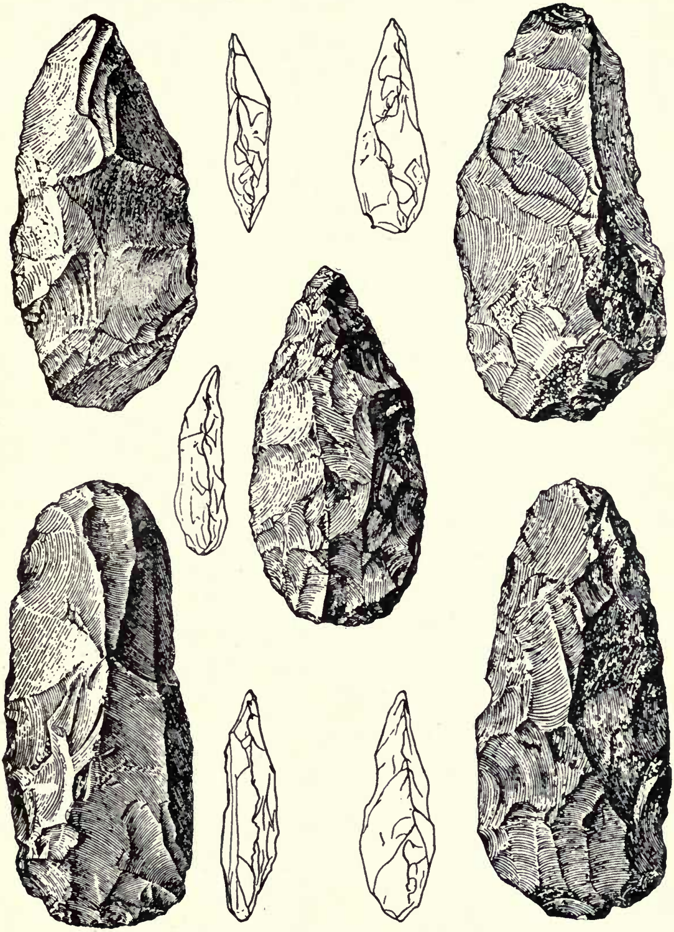
[1] Gr. *palaios* = ancient, and *lithos* = a stone.



PALÆOLITHIC IMPLEMENTS. (After Holmes.)

of primitive man were roughly chipped from blocks of flint, obsidian, chert, quartzite, aphanite, and other fine-grained rocks, but in the *Neolithic*[1] or *New Stone Age* they were ground and polished with much skill and patience.

(*b*) Neolithic = New Stone Age = Well-finished implements.
(*a*) Palæolithic = Old Stone Age = Roughly fashioned implements.

The Palæolithic and Neolithic represent stages of art development rather than periods of time. Hence the Palæolithic of one region may overlap the Neolithic of another. At the advent of Europeans, the Australian aborigines were still in the Palæolithic stage of art, and the Maori of New Zealand in the Neolithic. Neither of these isolated races was acquainted with the manufacture or working of the metals.

In Continental Europe and England there are numerous caves in which relics of Palæolithic man are associated with the remains of large extinct mammalia. In many cases the relics and animal remains are protected with a layer of calcareous stalagmite. This covering cannot always be regarded as an evidence of great antiquity, as calcareous sinters and stalagmitic deposits are known to accumulate with great rapidity in favourable situations. In the rock-shelters in the Waipara district in New Zealand, the bones of the sheep, introduced less than seventy years ago, have been found buried under an encrusting layer of calcareous stalagmite four inches thick. The evidence furnished by cave-deposits and river alluvia must always be subjected to critical examination before using it as the basis for important deductions as to the antiquity of man.

There is conclusive evidence that Palæolithic man was contemporary with several extinct mammals, which include the mammoth (*Elephas primigenius*), the woolly rhinoceros (*Rhinoceros tichorhinus*), the giant Irish elk with flattened horns (*Megaceros giganteus = hibernicus*), long-faced ox (*Bos primigenius*), hippopotamus (*Hippopotamus major*), the cave hyæna (*Hyæna spelæa*), and the cave bear (*Ursus spelæus*).

This association may mean either a considerable antiquity for man, or the existence of these animals up to a time not so very remote. The final solution of this problem has not yet been found.

One of the most important of recent discoveries relating to the antiquity of man was made by Eugene Dubois in a fossil-bearing stratum of drift on the left bank of the Solo, or Bergawan stream, near the centre of Java. The human-like remains, *Pithecanthropus*

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[1] Gr. *neos* = new, and *lithos* = a stone.

erectus, consist of the roof of a skull, a thigh bone, and two teeth, which were found associated with a rich fauna and flora. Of the mammalian fauna no less than 19 genera and 27 species were discovered, all of which are now extinct or greatly modified. But 87 per cent. of the Gasteropods found in the same bed are living species. Hence the drift with its remains cannot be older than Pleistocene.

Human remains were found in 1911 by the Yale Peruvian Expedition in the Cuzco Valley embedded in drifts under 75 feet of gravel. They were associated with the bones of several lower animals, and are believed to be of Pleistocene age.

In 1912 an important discovery of ancient human remains was made in a gravel pit near Piltdown Common, Fletching, Sussex. The gravel bed lies about 80 feet above the river Ouse, and less than a mile to the north of the existing stream. The deposit is about 4 feet thick, and consists mainly of water-worn fragments of Wealden ironstone and sandstone, with a few chert pebbles and a considerable proportion of water-worn flints derived from the Chalk of the South Downs. Portions of a human skull were found associated with a jaw of simian type, and the remains of an elephant, a mastodon, hippopotamus, and red deer, besides flint implements. The skull shows a high cranial development, but is believed by Keith to belong to a man of greater antiquity than the *Neanderthal* flat-skulled man of Germany, or the *Spy* man of Belgium characterised by enormous brow-ridges.

Among the most prolific bone caves or *hyæna-dens* in England are the famous Kirkdale Cave, near Kirkby Moorside, in Yorkshire; Dream Cave in Derbyshire; Banwell Cave in the Mendip Hills; Kent's Hole, near Torquay; and Cefn, near Denbigh.

In France caves rich in bones have been found near Montpellier and Narbonne; in Germany, between the Harz and Franconia; and in Austria, in Carniola and Hungary.

No Palæolithic remains are known in Scotland or the far north of England.

In North America Palæolithic and Neolithic relics are common in recent deposits, but they are not found in association with the large Pleistocene mammals as in Europe.

In Britain Neolithic relics are found in sand-dunes, caves, peat-bogs, swamps, and in tumuli which are now known to be the tombs of Neolithic man. The associated fauna is quite distinct from that of the Palæolithic age. Most of the large mammals have become extinct, but the Irish elk, reindeer, and bear, which no longer survive in England, were present, together with the fauna of early historic times.

Raised-beaches occur around all the continents, and may be observed on the shores of England, Scotland, Norway, Finland, France, Sicily, Italy, Egypt, East Africa, North Africa, Arabia, India, Malaysia, Australia, Tasmania, New Zealand, North and South America. The presence of these marine benches is an evidence of universal recession of the sea in quite recent times.

SUMMARY.

From the earliest Cambrian when the first assemblage of organisms appeared, there has been a continuous procession of life, receiving accessions of new forms at each geological stage until it grew into the majestic stream which now floods the Earth in such amazing wealth of animal and vegetable life.

(1) The *Eocene Period* is specially characterised as the dawn of existing life, and it is sharply separated from the Cretaceous by the absence of the Cephalopods *Ammonites, Belemnites, Hamites, Turrilites, Baculites*, etc., and of the reptilians *Ichthyosaurus, Plesiosaurus*, and huge Deinosaurs.

The stratigraphical unconformity between the Cretaceous and Eocene is not strongly marked, and is often difficult to distinguish; but the palæontological break is the greatest and most abrupt in the whole geological record.

The great Central Sea, *Tethys*, still stretched from the Atlantic to Further India. On its floor were accumulating thick deposits of Nummulitic Limestones and on its margin, piles of deltaic sands and muds of the *Flysch* facies of detrital deposits.

The volcanic forces which lay dormant during the whole Mesozoic era, but revived at the close of the Cretaceous, still continued to exhibit great activity in certain regions.

The dominating feature of the Eocene fauna is the advent of placental mammals, including ancestral forms of most of the large mammals of the present day.

The angiosperms or flowering plants which appeared in the Upper Cretaceous comprise the dominant vegetation in the Eocene forests, being represented by a great variety of Dicotyledons and Monocotyledons.

(2) The **Oligocene** is stratigraphically and palæontologically related to the Eocene, to which it properly belongs. It is mainly distinguished by the vast development of Foraminifera and reef-building corals.

The Central Sea is still a feature of vast geographical, geological, and meteorological importance; and on its northern shores the deposition of the deltaic sands and muds of the Flysch type continue to be deposited without interruption. At their outward limits the deltaic detritus is intercalated with the Nummulitic Limestone deposits formed on the floor of the deeper clearer waters of this great inland sea.

(3) The **Miocene** was a period of great geographical changes. It witnessed the uplift of the Pyrenees, Alps, Carpathians, Caucasus, and Himalayan Chains from the floor of the Central Sea, which thereby became reduced in size and broken up into large disconnected seas and inland salt-water lakes. It was at this time that the Mediterranean Sea, which is the last remnant of the great Tethys, was cut off from the Indian Ocean by the uplift of Syria, Asia Minor, Arabia, and Persia.

The Miocene fauna and flora show an increasing relationship to the life of the present time. The mammals now include the *Mastodon*, true elephant, the huge *Deinotherium*, rhinoceros, hippopotamus, deer, whales, dolphins, etc.

(4) In the **Pliocene** the Alps, Himalayas, and other great chains attained their full height; and the continents assumed their present forms.

Up till the middle of this period the climate of Northern Europe and North America was tropical or subtropical, but thereafter the character of the fauna and flora shows the approach, first of temperate, then of sub-Arctic cold. This gradual increase of cold was heralded by the southern migration of boreal forms into the temperate zones, both in Northern Europe and North America, and the migration of the southern forms into more congenial latitudes.

The fauna and flora of the Pliocene had already assumed a modern appearance, and 90 per cent. of the marine molluscs are living forms.

(5) The increasing cold culminated in the Pleistocene or Glacial Period, also called the Great Ice Age. In the early Pleistocene Northern Europe and North America were invaded by the northern ice-sheet. In Europe the ice-sheet radiated outwards in all directions from the highlands of Scandinavia, and at the same time the Alpine glaciers crept down their valleys to the foothills and plains.

The Scandinavian ice-sheet bridged the Baltic Sea and filled up the North Sea as far south as the English Channel. The land-ice radiating from the Scottish Highlands flowed into the North Sea and fended the Scandinavian ice from the mainland; but in England the Scandinavian ice rasped the north-east coasts, and, flowing down the Wash gulf, overflowed East Anglia and the adjoining counties. Wherever it touched land it left a trail of Scandinavian erratics.

The Scottish land-ice flowed southward into England as far as York; and on the west coast filled the Irish Sea, which it descended till abreast of the Bristol Channel. It surged over the highest peaks in the Isle of Man, 2000 feet above sea-level; and sent a huge stream through the Lancashire Plain into Central England and basin of the Severn. The division of the Scottish ice on the west coast was due to the resistance offered by the Welsh mountains and their cap of land-ice.

The Pleistocene Period is divided into three stages, namely, the *Advancing Stage, Maximum Stage,* and *Retreating Stage.* That is, the Ice Age began and ended in local glaciers, which became confluent during the maximum stage of refrigeration.

The Advancing Stage was characterised by the deposition of vast deposits of fluvio-glacial drifts formed in front of the descending Alpine glaciers and advancing northern ice-sheet.

At the extreme limits reached by the ice during the period of maximum refrigeration, at the place where the ice-edge halted, there was frequently piled up high mounds and ridges of morainic material and widespreading valley-trains.

During the retreat, the ice scattered a sheet of boulder-clay or ground-moraine in its wake, forming a deposit that spread over hill and dale. Where the ice-face was drained by glacial streams or rivers, the boulder-clays were partially re-sorted and associated with fluvio-glacial drifts that frequently contain the remains of large extinct mammals. During minor advances of the ice, these drifts were sometimes covered over with morainic detritus, and thus became intercalated in the ground-moraines.

Throughout the retreat, fluvio-glacial drifts were continually deposited in front of the ice-edge, forming what are called the *Newer Glacial Drifts* to distinguish them from the *Pre-Glacial Drifts* formed during the advancing stage.

(6) The **Recent or Human Period** is specially characterised by the advent of Man, whose relics are found in caves, drifts, and peat-bogs associated with some large extinct mammals, such as the woolly mammoth, woolly rhinoceros, great Irish elk, cave-hyæna, and cave-bear.

The Recent Period is divided into three main stages, namely :—

3. Iron Age.
2. Bronze Age.
1. Stone Age.

The *Stone Age* is subdivided into two sub-stages, the Palæolithic and Neolithic.

The *Palæolithic* was the age of rough, rudely fashioned implements, and the *Neolithic* the age of well-finished and polished implements.

Raised-beaches occur around the coasts of all the great continents and islands, and indicate a general recession of the sea in comparatively recent times.

CHAPTER XXXIV.

DEVELOPMENT OF SURFACE FEATURES.

The development of surface forms is mainly dependent (*a*) on the character and arrangement of the rocks, and (*b*) on the climatic conditions. Of these the last is perhaps the more important.

When we broadly view the surface configuration of the Earth, we have no difficulty in distinguishing two outstanding types of surface form, namely :—

I. *Arid Erosion* type.
II. *Pluvial Erosion* type.

Arid Erosion Type.—Arid erosion may be defined as the degradation of the land by subaerial agencies where the annual rainfall is less than 18 or 20 inches. Its effects are best seen where the rainfall is confined to a few months in the year.

Arid erosion acts uniformly on all the surfaces exposed to the action of the atmosphere, but, owing to the effects of desert winds and gravitation, it is more energetic on the prominent land-features than elsewhere. Hence its general effect is to reduce the whole surface of the land to a plateau or base-level of low relief. The plateau form of feature is typical of arid erosion in all continental areas.

Good examples of plateaux of arid erosion may be seen in the high veldt lands of South and Central Africa, in the desert regions of the Western States of North America, in the sandy wastes of Arabia, Central Asia, and Mongolia, and in the high undulating forest-covered interior of Australia.

In South and Western Australia the edge of the great plateau is buttressed by great descending spurs and ridges frequently surmounted by what appear to be prominent mountain-peaks. Hence, when viewed from the sea-border, the edge of the plateau presents the configuration of a mountain-chain. The same rugged outline and Alpine effect is seen on the edge of the high veldt-lands of the Orange Free State and Transvaal when viewed from the Natal border.

A peculiarity of arid and semi-arid regions is the circumstance that many of the boulders and fragments of stone lying on the surface have become coated on the outside with a bluish-black shining glaze or enamel, consisting of manganese and iron oxides, mostly the former. The stones usually glazed in this way are basic and semi-basic igneous rocks and greywackes; and where such are abundant, the black stones impart a burnt aspect to the landscape. The exposed surfaces of siliceous cement stones, which consist of sands that have been cemented into a solid rock by the infiltration of siliceous waters, and of siliceous sinters frequently become glazed with a vitreous enamel of silica. The formation of these enamels is apparently the result of chemico-capillary action.

The characteristic colour of arid landscapes is a warm yellowish-red hue arising from the peroxidation of the iron contained in the rocks. Desert sands and dust are characteristically red, frequently brick-red.

Pluvial Erosion Type.—The general tendency of rain, frost, and other subaerial agencies of denudation is to degrade the whole surface of the land; but the erosive effects of rain, in the form of brooks, streams, and rivers, is to wear away the surface faster in one place than in another. The streams will naturally follow fractured and faulted zones rather than excavate channels through solid rock, and they will erode soft rock-formations faster than hard. The general effect of this differential rate of denudation will be the gradual development of a variety of surface features, the form of which will be dependent on the character and arrangement of the rocks, the amount of the rainfall, and the velocity of the streams; and this last will be governed by the height of the land relatively to its base-level.

As erosion proceeds, the harder masses of rock will be left standing above the general level of the country, and they may form hills, ridges, or even mountains. In gently folded strata the harder bands of rock will form prominent lines of escarpment. Where gently-inclined strata are intersected by a strike-fault, the harder bands will form ridges with a steep descent into the fault-valley on the one side and a long gentle dip-slope on the other.

In a previous chapter we found that a rock-formation representing a cycle of deposition is generally closed by a bed of limestone. In folded or faulted strata it is this calcareous member which usually forms the prominent escarpments or declivities of a landscape.

When a rock-formation contains a number of hard bands of limestone, conglomerate, or sandstone separated by clays, marls, or other soft rock, the outcrops of the hard bands not infrequently stand out as conspicuous escarpments that can be traced by the eye for many miles as they contour around the ridges and mountain slopes.

Generally speaking, the denudation of formations composed of clays, marls, shales, chalk, or soft sandstones produces gentle slopes and smooth outlines, even when the beds are steeply inclined. Conversely, the denudation of hard rocks, and particularly of hard rocks alternating with soft, usually develops rugged outlines, more particularly where the strata are tilted at high angles. But a cycle of denudation has its stages of infancy, maturity, and old age; hence the character of the sculpturing as presented to the eye will depend on the progress made towards maturity or old age.

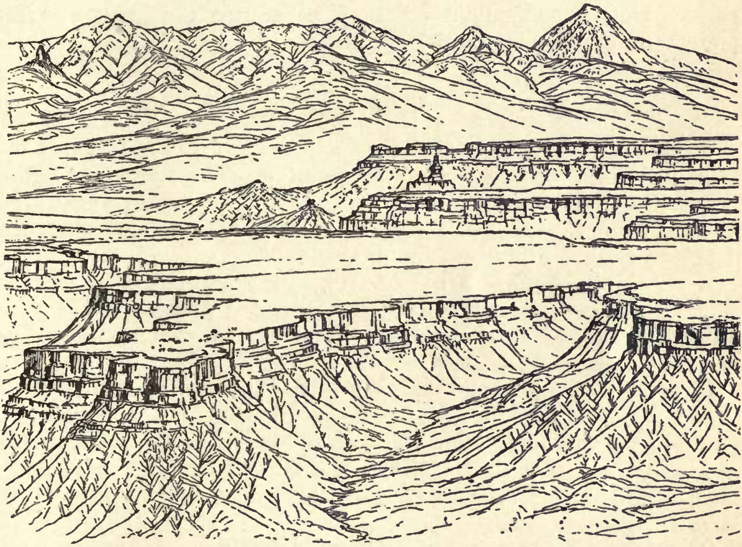


FIG. 221.—Showing erosion of plateaux in cretaceous rocks. (C. E. Dutton, *U.S. Geol. Survey.*)

In a region occupied by a great thickness of mica-schist occurring in isoclinal folds, the rock in the infantile stage of erosion will be carved into V-shaped valleys and tent-shaped ridges. At a later stage the valleys will be widened and the ridges rounded; and in the decadent stage we shall get an area of gentle slopes and low relief, not distinguishable in configuration from the rolling downs composed of clays, marls, or shales.

As with mica-schist, so it is with slate or gneiss. Even a granite massif may form a bold mountain dominated with gigantic tors or a flat swampy moorland.

In regions that have been overrun with land-ice, the contours are softened and rounded. In Alpine valleys lakes may be formed by morainic barriers, and crescent-shaped piles of glacial débris scattered over the plains and foothills.

But pluvial denudation is not always destructive. When constructive, it is responsible for the development of many minor surface features, among which may be named the great alluvial plains and deltas that border the sea.

Mountains.

A mountain may be defined as a hill or ridge that rises conspicuously above the surrounding country. The term is in some respects a relative one, for the ridge that would form a conspicuous mountain on the plains of Prussia might sink into insignificance if placed among Alpine surroundings.

A mountain-chain is a narrow ridge or a succession of narrow ridges running more or less parallel with one another. The prominent peaks on a mountain-chain are often called mounts or mountains.

If we look at a physical map of the Earth, we shall find that (*a*) the continents are in general bordered with mountain-chains, and (*b*) that the highest border faces the larger ocean. The girdle of mountain-chains that encircles the Pacific Ocean is a striking illustration of this type of continental fringe, and, moreover, it faces the greater ocean.

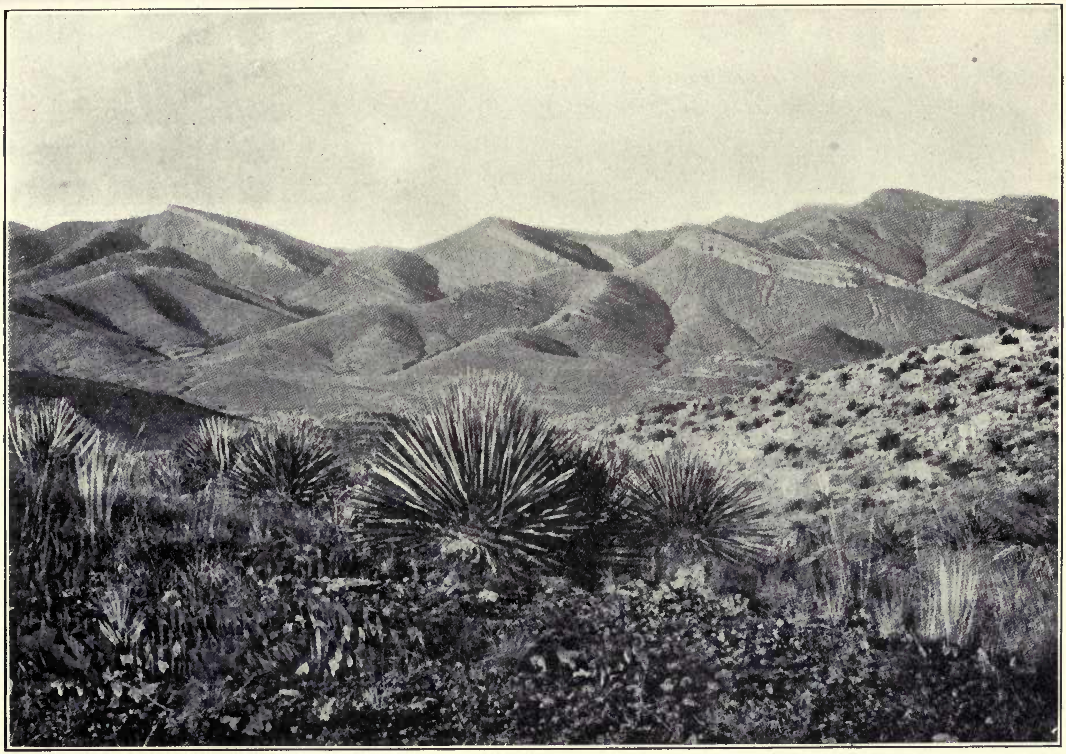
Origin of Mountains and Mountain-Chains.—Mountains and mountain-chains have originated in various ways, and, according to their origin, they may be divided into four classes :—

(1) *Folded Mountains*, i.e. the *Alpine type.*
(2) *Volcanic Mountains.*
(3) *Plateau-Mountains.*
(4) *Residual Mountains.*

Folded Mountains.—This type includes all the great mountain-chains of the globe which are now known to consist of uplifted crustal folds ; hence the origin of the distinctive name *Alpine* by which this type is sometimes not inappropriately designated.

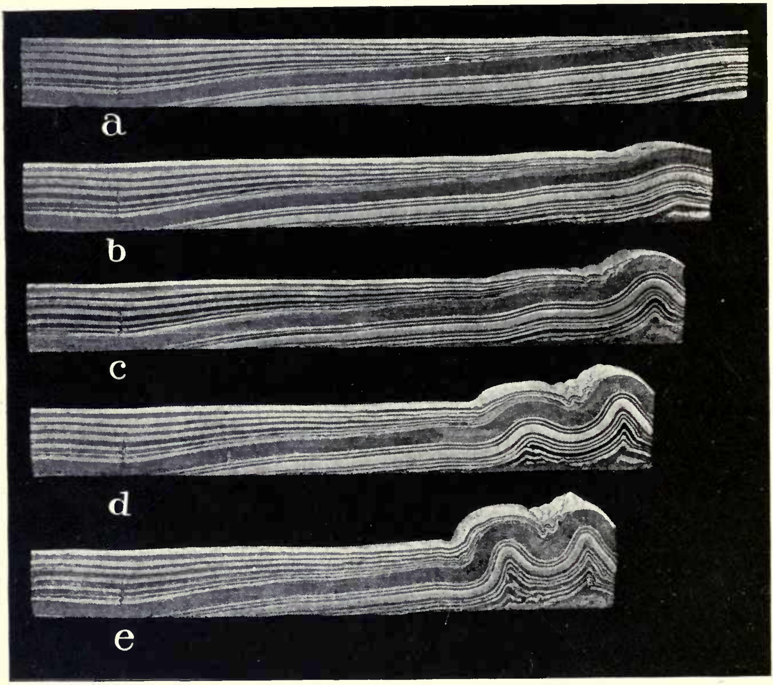
To this type of folded chain belong the Andes, Rockies, Sierras, Appalachians, Alps, Pyrenees, Carpathians, Urals, Himalayas, and New Zealand Alps.

The folding has been caused by lateral compression or thrust



HILLS CARVED FROM CRETACEOUS BEDS, EAST OF BISBEE. (U.S. Geol. Survey.)

View is northward across Mule Gulch. The prominent white band is the upper member of the Mural limestone, forming the top of Mural Hill on the left and showing the dislocation due to the Mexican Canyon fault.



REPRESENTATION OF WILLIS' EXPERIMENTS IN THE ARTIFICIAL PRODUCTION OF MOUNTAIN FOLDS, WITH LAYERS OF WAX OF DIFFERENT COLOURS. (U.S. Geol. Survey.)

arising from the contraction of the Earth's crust. The most obvious result of compression is the shortening of the area occupied by the strata.

The geological investigations of Nicol, Lapworth, Peach, Horne, and others in the North-West Highlands of Scotland have proved conclusively that sharp folding is always accompanied by fracture and faulting; and sometimes by extraordinary horizontal shear, whereby overriding sheets of rock may be overthrust many miles from the place where they were formed. By a series of pressure experiments in 1888, Cadell obtained instructive imitations of the tectonics[1] of mountain-building, overthrust, and infolding of strata.

The forms of folded or tectonic mountains in their juvenile stages of existence are in a measure an expression of their structure. The ridges coincide with the anticlines, and the valleys with the synclines or downward folds. This juvenile structure is well exemplified in the Swiss Jura, which consist of four main parallel ridges, each dominated by an anticlinal fold, as shown in fig. 222.

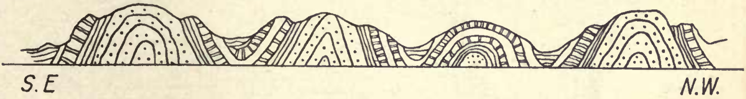


FIG. 222.—Showing symmetrical flexures of Swiss Jura. (After Clerc.)

With increasing age, and as the effects of denudation become greater and greater, the coincidence between folding and configuration becomes less and less, and finally disappears.

In the Appalachian Mountains in Pennsylvania, denudation has progressed so far that the valleys follow the anticlines, while the ridges coincide with the synclines, which resist denudation more effectually than anticlines.

The mountains in time become remodelled by erosion; and the new configuration is determined by the character and arrangement of the rocks, and the climatic conditions. Such ancient tectonic mountains may therefore be so modified by erosion as to be difficult to distinguish from the type of mountains called *residual*. Many folded mountain-chains existed, of which only the worn-down stumps now remain. They have been truncated by the erosion in past geological ages, and partly buried under the detritus derived from their own destruction.

Volcanic Mountains.—These are hills or ridges piled up by the accumulation of lavas and other material ejected from a volcanic vent or fissure.

Volcanoes may rise from the floor of the sea, from a plain or

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[1] Gr. *tekton* = builder.

plateau, or from the crest of an Alpine chain, as many do in the Andes of South America. They may occur as isolated mountains or in groups of mountains, each with its own crater, or in considerable chains.

Volcanoes of late Tertiary date generally retain their original form, modified perhaps to a small extent by recent fluviatile erosion, but the older piles of volcanic rocks have in most cases been so deeply eroded that they now present all the features and sculpturing of mountains formed by erosion.

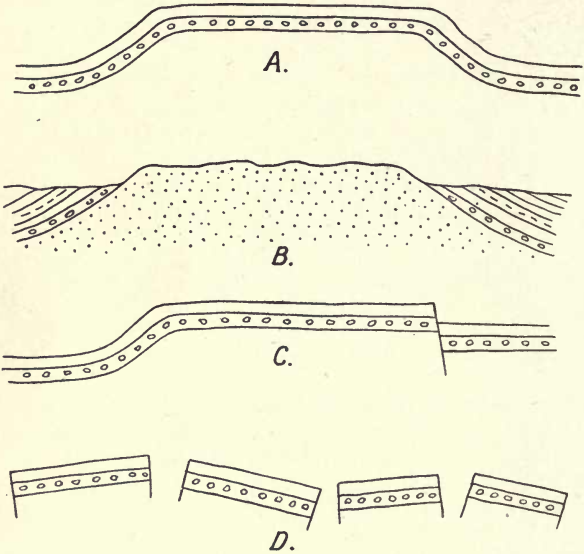

FIG. 222A.—Types of plateau-mountain structure. (After Powell, modified by Rastall.)

(*a*) Uinta type.
(*b*) Park Plateau type.
(*c*) Kaibab type.
(*d*) Block-mountain type.

Plateau-Mountains.—These are subordinate in extent and grandeur to the great alpine chains composed of uplifted folds, but they present some features of peculiar interest in connection with crustal movements. In Colorado and Utah, where plateau-mountains are well developed, four types of structure have been recognised by Powell and other members of the Geological Survey of the United States.

(1) *Uinta Structure.*—This type of structure is typically developed in the Uinta Mountains of Utah and Wyoming. It consists of two large monoclinal flexures bending in opposite directions, each

with the downthrow on the external side, thus leaving a broad plateau-like mountain between them (fig. 222A, A). In some places the strata in the line of maximum flexure have given way, and here the bending stress has been relieved by fracturing, accompanied by profound faulting.

(2) The *Park Plateau Structure* is found in the Yellowstone Park region of Wyoming, where a thick series of Mesozoic rocks has been bent over a plateau-like complex of granites and gneisses, and afterward denuded, thereby leaving their truncated ends standing up at high angles against the flanks of the central mass of older rocks (fig. 222A, B).

(3) The *Kaibab Structure*, is related to the Uinta structure, of which it is merely a modification. It consists of one dominant monoclinal flexure, and a powerful fault which dislocates the upraised horizontal strata (fig. 222A, C).

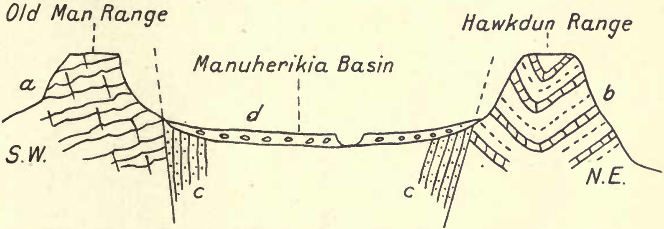

FIG. 223.—Showing block-mountains of Central Otago, N.Z.

(*a*) Mica-schist.
(*b*) Triassic sandstones and shales.
(*c*) Middle tertiary lacustrine beds.
(*d*) Pleistocene gravels.

(4) *Block-Mountains.*—This type owes its origin to the displacement of large blocks, or segments, of the crust along the track of gigantic faults. Typical structures of this class are found in Colorado and Utah, and in Central Otago, New Zealand, all in arid plateau regions.

This structure is produced when a broad and lofty plateau, or elevated peneplain, is broken into blocks by profound faults. In the Great Basin region, lying between the Sierras and Rocky Mountains, the blocks are tilted at various angles (fig. 222A, D); but in Central Otago they have maintained a nearly horizontal position, and are separated by wide rift-valleys or *graben*.

Horsts.—For well-defined blocks that have remained as elevated masses while the areas around them have sunk, Suess has used the German term *horst*. Such fixed blocks are closely related to *block-mountains*. Typical examples are the mountains of the Vosges and Black Forest, which owe their existence to the subsidence of the segment which now forms the rift-valley of the Rhine.

Large portions of Australia, of Central and South Africa, have been land areas since the earliest times, and may be looked upon as forming horsts of continental dimensions. These immovable blocks are mostly composed of complex masses of crystalline rocks, and in a large measure they have controlled and directed the lateral crustal movements of younger Palæozoic and later times. They have formed the *thrust-blocks*, or anvils, against which the unaltered sedimentary formations have been crushed, folded, and sheared.

Similar unyielding blocks occur in the Alaskan and Laurentian regions; and on a smaller scale we have the crystalline block forming the substructure of Great Britain, with its protruding domes in the Southern Uplands and Northern Highlands of Scotland. Nearly antipodal to this there is the New Zealand crystalline block, to the existence of which the distant Dominion owes its oceanic character.

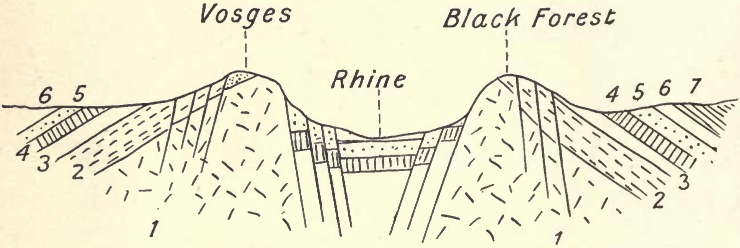

FIG. 223A.—Showing the Rhine flowing in a Rift-valley.
1, Granite. 2–7, Mesozoic rocks. 8, 9, Tertiary and Recent.

Residual Mountains.—These are formed by the removal of the surrounding country by erosion. Residual mountains and ridges therefore owe their existence to their ability to resist denudation.

When a high plateau has been deeply dissected by the erosion of considerable streams and rivers, the portions that have escaped destruction may sometimes form a complex of ridges and mountains with narrow crests and projecting peaks. As a rule, residual mountains do not occur in continuous chains like the Alpine type, nor do they show any symmetrical arrangement. On the contrary, they generally occur as a tumble of isolated ridges and mountains.

The Highlands of North Scotland are a good example of mountains of the residual type. A study of their structure shows that they are merely the remnants of the ancient Caledonian plateau, that itself represented the stump of a still more ancient folded mountain system.

Origin of Plateaux.—Plateaux are elevated tablelands possessing

a more or less undulating surface. Genetically they may be arranged in three dominant groups :—

1. Plateaux of arid erosion.
2. Basaltic plateaux.
3. Block-plateaux.

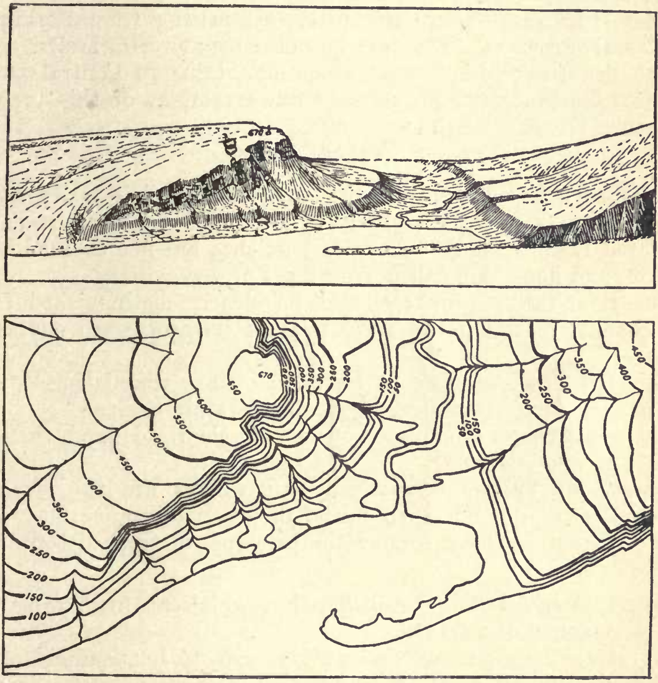

FIG. 224.—Sketch and corresponding contour map, *U.S. Geol. Surv.*

Plateaux of Arid Erosion.—An elevated region that has been subjected to subaerial erosion in an arid region in time becomes worn down to a plateau or peneplain. Typical plateaux of this kind occupy nearly the whole of the interior of the Australian continent. They appear almost level when viewed in distant perspective, but when travelled over are found to be diversified with rocky knobs, minor elevations, river gorges, and fault-escarpments.

Many of the prominent mountains, as seen from the coast, are only the scarps of the inland plateaux.

The plateaux which occupy the interior of South and Central Africa are high peneplains of arid erosion.

Basaltic Plateaux.—These have been formed by floods of basaltic lavas that have issued from volcanic vents of the fissure type. Familiar examples are the Snake River Plains in Western North America, Deccan plateau of Central India, and the basaltic plateau of Victoria.

Block-Plateaux.—These are platforms arising from the uplift of crustal segments. They are bounded by powerful faults.

The beautiful table-topped block-mountains in Central Otago in New Zealand are remarkably fine examples of this type of plateau.

Valleys.

The term *valley* is applied to the longitudinal hollow or depression through which a stream or river flows. In arid and recently-glaciated regions many valleys and gulches are not drained by a stream, and hence are called *dry-valleys* or *dry-gullies*.

The river-valley proper should be clearly distinguished from the channel in which the river pursues its downward course to the sea.

The valley proper may be bounded by low undulating downs, low foothills, high foothills, ridges, or mountain-chains.

When the ridges bounding a valley are clearly defined, they are called the *valley-walls*.

Genesis of Valleys.—Practically all valleys are the work of subaerial erosion; but their initial direction or course may arise from different causes. Among the principal of these determining causes are:—

- (*a*) *A powerful fault* or dislocation which at first forms the channel of a rivulet.
- (*b*) *A series of parallel faults* giving rise to longitudinal strips of sunken areas, forming what are called *rift-valleys* or *graben*. The stationary areas forming the valley-walls have already been described as *horsts* or *block-mountains*.
- (*c*) *A shear-zone* along which the country-rock may be so shattered and broken as to be easily attacked by fluviatile or arid erosion.
- (*d*) *Earthquake and volcanic rents.*—The great fissure-rent formed by the Tarawera eruption in 1886 has become the channel of a considerable stream, and is already assuming the dimensions of a well-defined immature valley. Earthquake rents that coincide with old fault-lines have in many regions become stream channels that will in time develop into valleys.

(*e*) *Zones of soft rock* bounded by hard rock, giving rise to what may be called differential erosion by pluvial, glacial, or arid agencies. While the direction of most trunk-valleys is probably determined by faulting or some other structural cause, it is certain that the direction and existence of most of the numerous lateral valleys is due to differential erosion. A soft series of strata may be repeatedly brought to the surface by acute folding or faulting, giving rise to the formation of a number of more or less parallel valleys bounded by steep escarpments.

Fault-scarps may become so indented by erosion as to be no longer parallel to the original fault-line.

(*f*) *Simple synclinal folding* in recently-disturbed areas. It is not often that the surface configuration coincides with the underground arrangement of the strata; and this is seldom seen except in immature valleys where the amount of erosion that has taken place since the folding of the strata is insignificant.

Soundings undertaken during recent years have brought out the striking fact that the submarine continuations of many rivers can be traced to the edge of the continental platform, where they descend through narrow gorges into the abyssal floor of the ocean. Notable examples of rivers whose courses can thus be traced are the Congo, Tagus, and Shannon. These submarine troughs would indicate a considerable subsidence of the eastern Atlantic borders. always provided they are true valleys of subaerial erosion, and not the seaward continuation of rifts or *graben* resulting from faulting.

The deep gutter which passes through the Moray Firth probably marks the course of the glacial Spey when it ran northwards and joined the older and greater Rhine.

A deep groove surrounds the coast of Norway, and cuts off that region from the shallow plateau of the North Sea. It is a geographical feature of great interest, but its meaning and origin are not yet well understood.

Probably all great valleys are connected with powerful crustal dislocations.

Rift-Valleys.—These frequently form physiographical features of vast importance. Perhaps the most remarkable is the great rift-valley of Syria and the Red Sea. This depression forms the valley of the Jordan and the basin of the Dead Sea, the surface of which lies 1300 feet below the level of the Mediterranean. From the Dead Sea it pursues a southerly course down the Gulf of Akaba, and curving to the south-east, forms the trough of the Red Sea.

The Shire Valley and Lake Nyasa form the southern portion of one of the greatest rifts in the African Continent. This depression, with a break at the north end of Nyasa, runs northward for 400 miles through Lakes Rukwa and Tanganyika; and with a few short breaks passes through Lakes Kivu, Albert Edward, and Albert, and thence on to the Nile.

Fault-Valleys.—Most Alpine chains are intersected by deep transverse valleys that cut back to the main divide, and end in a pass, saddle, or *col*. Across the pass there is frequently another valley which intersects the range on the opposite side. In many cases it is possible to cross a high inaccessible chain by ascending one valley and descending the opposite one.

The two valleys which meet at the pass as a rule follow the course of a powerful fault or shear-zone running transversely across the main chain. Such valleys are dislocation rifts widened out by subsequent erosion, and hence are essentially different from the *graben* or strips of subsidence already described.

Canyons.—In the canyon region of Colorado the horizontal, Cretaceous and older strata form an ancient plateau which has become intersected by numerous deep gorges formed by fluviatile erosion (see Frontispiece). The canyons do not follow faults or lines of dislocation. In the beginning they were probably simple joint fissures that gradually became enlarged by chemical and mechanical erosion.

The great depth, narrowness, steepness, and U-form of the canyons show that the excavation has been relatively rapid. Moreover, the cycle of erosion is still in the juvenile or torrential stage.

Form of Valleys.—The form of practically all valleys has been modified by pluvial or glacial erosion, or by the united activity of both, or by arid erosion. Subaerial erosion will always be greatest where the rocks are softest, or where they are so broken as to offer the least resistance.

The form of the cross-section of a valley at any point will depend on the maturity of the valley, the resistance offered by the rocks, and the character of the eroding agency.

In a juvenile valley the cross-section will be V-shaped; and in the uplands the river will occupy the whole width of the floor of the valley, in the torrential portion of its course running in a narrow gutter excavated in the solid rock, and in the middle portion wandering over a wide shingle-bed which may vary, according to local circumstances, from a few yards to many miles wide.

In a river-system which has reached maturity the valley is wide and the walls are not very clearly defined. In this portion of its course the river usually occupies a well-defined channel.

A typical river-system usually exhibits three phases or tracts of erosion, namely: (*a*) a *torrent-tract*, where erosion is at a maximum and deposition at a minimum; (*b*) a *valley-tract*, where the gradients are flatter and erosion consequently slower—here also the valley-walls are flatter and deposition of detritus is taking place in favourable situations; (*c*) the *plain-tract*, where erosion has practically ceased and deposition is at a maximum.

Obviously the *plain-tract*, which has been subjected to erosion the longest, shows the flattest gradients and lowest relief. In the *torrent-tract*, which comprises the latest territory added to the river-system—the frontier, where the tributaries are continually extending their sphere of influence—the contours are steep and rugged.

As erosion proceeds, the plain-tract encroaches on the valley-tract, and the valley-tract on the torrent-tract, which in its turn is continually reaching out into new territory. It is in the plain-tract that a river-system first reaches its base-level of erosion.

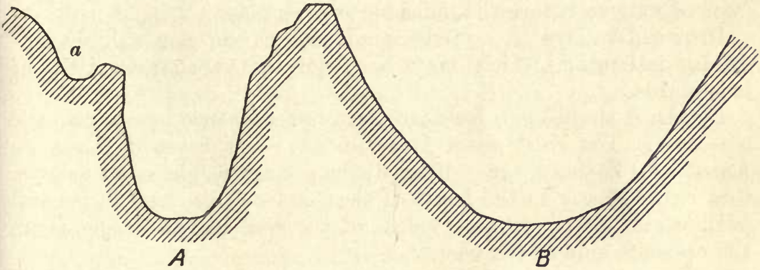

FIG. 225.—A, Cross-section in hard rock with corrie lake on high shoulder at *a*; B, Gentle slope in soft rock.

Glaciated-Valleys.—Glaciated-valleys are usually distinguished by flat bottoms and smooth even walls. In relatively soft rock the projecting spurs or ridges are faceted so as to present tent-shaped ends; but where the rock is hard, the ice may ride over the spurs, the crests of which are truncated into flat platforms.

Ridges of hard rock running parallel with the axis of the valley are usually worn into rounded whale-backed ridges or *roches moutonnées*.

The form of the cross-section of a glaciated-valley depends mainly on the hardness of the country-rock. Where the rock is granite, gneiss, or hard crystalline schists, the form approaches the U-shape; but where the rocks are soft schists, shales, or Tertiary strata, the walls are worn into gentle catenary curves. These forms are shown in fig. 225.

Drowned-Valleys.—When subsidence takes place in a maritime region intersected by deep valleys, the sea advances and floods the valleys, which thereby become converted into *sounds*, *fiords*, and *sea-lochs*. These partially submerged or *drowned-valleys* as they are called, possess the same contour forms below sea-level as above.

The beautiful fiords of Norway, Alaska, and New Zealand, with their numerous ramifying arms and inlets, are typical examples of drowned valleys that have been modified by glacial erosion.

The fiords of Norway and New Zealand, and the sea-lochs of West Scotland, are usually deeper inside than at their mouths. The cause of this deepening may arise in some cases from accumulations of glacial débris deposited at the sea-face of the tongues of ice that occupied the valleys at the close of the Pleistocene; in others from the presence of lake-basins or depressions in the floor of valleys before the subsidence took place.

Drowned-valleys in non-glaciated regions do not exhibit this inside deepening, which may be regarded as characteristic of true fiords.

Fiords, it should here be noted, are not a feature peculiar to the sea-coast. The *fresh-water fiords* on the west coast of Lake Te Anau, New Zealand, are profoundly deep, narrow, glaciated valleys. that extend back to the heart of the Alpine chain, and in general outline and character are typical of the well-known *sea-fiords* on the opposite side of the chain.

Lakes.

A lake is a body of water entirely surrounded by land. The term is usually restricted to sheets of water sufficiently large to form physiographical features of some importance. The smaller bodies of water are called *tarns*, *meres*, *corrie lakes*, and *pools*.

Genetically considered, lakes and tarns may be classified in five main groups :—

(1) Tectonic lakes, or lakes due to differential earth-movement.
(2) Glacial lakes.
(3) Barrier lakes.
(4) Crater lakes.
(5) Dissolution lakes.

Lakes due to Differential Earth-Movement.—This class comprises the largest and most important sheets of water, which, acording to local conditions, may be salt, brackish, or fresh. As a rule they are situated in plains or plateaux.

The Caspian Sea and Sea of Aral, which occupy portions of the same crustal depression and were at one time united, are good examples of inland salt-water lakes that have been detached from the ocean by crustal movement. The faunal evidence seems to point to a former connection with the Arctic Ocean, and the physiographical evidence to a connection with the Black Sea depression. The mean water-level of the Caspian Sea is 84 feet below that of the Black Sea; and of the Sea of Aral, 128 feet above that datum—differences of level which may be ascribed to crustal warping.

Estuaries and arms of the sea that have become detached by uplift or crustal tilting may increase in salinity in arid regions, or become fresher in regions where the inflow of fresh water exceeds the evaporation. Conversely, a freshwater lake in a region of increasing aridity may become saline and in time present many of the features of a salt-water lake that has been cut off from the ocean.

The Dead Sea lying in the depression of the Syrian Rift-Valley is extremely saline, while the great lakes situated in depressions along the course of the East African Rift-Valley are fresh. The Great Salt Lake of Utah situated in the Great Basin is merely the shrunken remnant of a large inland lake that owed its origin to crustal deformation.

Glacial Lakes.—These are situated in recently glaciated regions, and, as a rule, occupy depressions in narrow Alpine valleys. Good examples are Lakes Como and Maggiore on the Italian side of the Alps, and Lake Wakatipu in New Zealand.

Glacial lakes frequently occupy rock-basins which may be many hundred feet deep; but the depth of most lakes of this class is increased by barriers at the outlet composed of morainic and fluvio-glacial detritus.

The erosive effect of a glacier is proportional to the thickness of the ice. A stream of ice, like a river, tends to elongate and deepen the depressions in its bed. In this way certain parts of glacial valleys have become overdeepened, and now form lake-basins.

The erosive effect will be greatest in soft strata, or in zones of rock crushed and broken by faulting or shearing.

Many corrie lakes that occupy niche-like indentations on the brow of mountain slopes and on the flat shoulders of valley-walls, rest in rock-basins that were excavated by ice during the Glacial Period.

Barrier Lakes.—Some Alpine lakes have been formed by the blocking up of the valleys by glacial detritus; but most Alpine lakes, as mentioned above, are partly barrier and partly rock-cut.

The circular tarns or corrie lakes found in glacial cirques are frequently held up by accumulations of snow-piled rocky detritus, but many occupy true rock-basins.

Barrier lakes are sometimes formed in mountainous regions by extensive land-slips, avalanches, or ice-jams, but they do not form permanent geographical features.

Marginal Glacial Lakes.—When a continental ice-sheet advances across the divide separating one watershed from another, the drainage from the ice-front will flow down the invaded valleys without hindrance, and where the topographical features are favourable, wide valley-trains of fluvio-glacial drift may be formed. But when the ice retreats behind the dividing range, the drainage will be dammed between the high land and the ice-front, thereby forming a marginal lake which will increase in size and depth as the ice-recession progresses, till a natural outlet is formed. The site of such glacial lakes will be marked by high-level beaches and lacustrine deposits.

Many fine examples of Pleistocene glacial lakes existed in the Laurentian Lake Region of North America, along the ice-front of the Keewatin and Labradorian ice-sheets.

When the Mesabi and Giants ranges were completely covered with ice, and the ice-front lay to the south of these transverse barriers, the drainage passed down the Mississippi Valley; but when the ice-sheet retreated into the Lake Superior basin, on the north side of the dividing ranges, the drainage was held up between the high land on the south and the retreating ice, thereby forming great marginal lakes, the largest and most notable of which has been called Glacial Lake Agassiz, so named after the distinguished Swiss naturalist Agassiz, who was the first to recognise the evidences of a Pleistocene extension of the Arctic ice-sheet in northern continental Europe and Scotland. As the ice-sheet receded Lake Agassiz grew in size, till the whole lacustrine area, as estimated by Warren Upham,[1] exceeded 110,000 square miles or more than the united area of all the present Laurentian lakes.

The three detrital terraces or benches, forming what are known as the *Parallel Roads* of Glen Roy in the Highlands of Scotland, are believed by some writers to be the beaches of a lake formed by a barrier of glacier-ice.

Rivers are sometimes blocked at their mouth by ridges of wind-blown sands, whereby large shallow lagoons or basins are formed near the sea. In some maritime regions the mouths of the rivers are blocked by wide stretches of shingle cast up by powerful tides. Many capacious lake-like harbours of great value have been formed in this way on exposed storm-beaten coasts.

Crater Lakes.—These occupy the craters of extinct or dormant volcanoes. Good examples of these may be seen in the Eifel, Auvergne, Central Italy, and North New Zealand.

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[1] *The Glacial Lake Agassiz,* Monograph xxv., U.S. Geol. Survey, 1894, p. 214.

The depressions formed by explosive volcanic outbursts frequently form lakes of considerable extent. Lake Rotomahana in New Zealand occupies a portion of the great fissure-rent formed by the Tarawera eruption in 1886. In the same region many large lakes, notably Lakes Taupo and Rotorua, have been formed by local subsidence in the neighbourhood of old centres of eruption situated on the Central Volcanic Plateau.

The lavas and ejectamenta of volcanic eruptions have in some cases formed barriers across valleys whereby the natural drainage has been impounded, thereby forming lakes. The Yellowstone Lake is confined by a barrier of lava, and also the Lac d'Aydat of Auvergne.

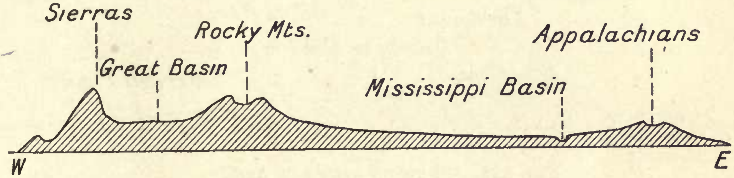

FIG. 226.—Showing profile of North America.

Dissolution Lakes.—These are formed in limestone regions, and arise from the dissolution of the limestone by the carbonic acid contained in the ground water. It is probable that most of the lakes in the limestone districts of Ireland belong to this class.

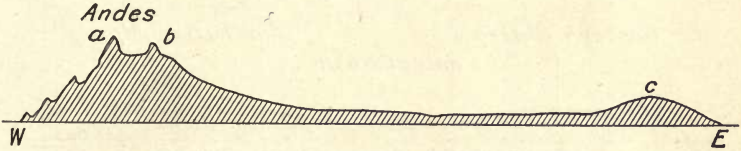

FIG. 227.—Showing profile of South America.

Continental Forms.

When we take a broad survey of the great continents, we are impressed with certain outstanding physiographical features that seem to suggest a relationship between the continents and the bordering oceans. This relationship has been expressed by Dana in two postulates as follows :—

(1) The continents have in general elevated mountain borders and a low or basin-like interior.

(2) The highest border faces the larger ocean.

America.—In North America we have the Rocky Mountains on the Pacific side (the side of the greater ocean), and the Appalachians on the Atlantic side. Between these chains lies the great interior plain.

In South America the great Andes Chain faces the Pacific (the larger ocean), and a low coastal range faces the Atlantic.

The Bolivian plateau lies between the Western Cordillera (*a*) and the Eastern or Bolivian Cordillera (*b*); while on the east coast we have the low ranges of Venezuela and Guiana.

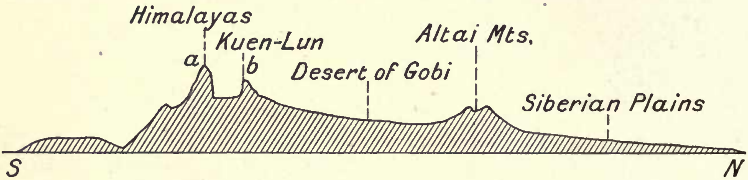

FIG. 228.—Showing profile of Asia.

Europe.—This continent does not present the well-defined coastal arrangement of the mountain-chains of North America. Moreover, the great chains, as in Asia, follow a general east and west course.

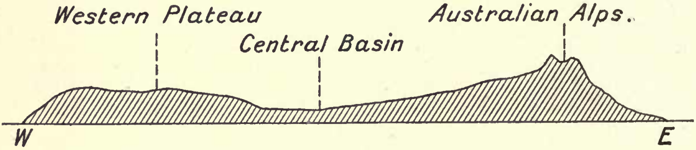

FIG. 229.—Showing profile of Australia.

On the south side of Europe we have the Pyrenees, Alps, Carpathians, and Caucasus; and on the north the mountains of Scandinavia. Between these lies the Baltic depression, the vast plains of North Germany, and Baltic provinces of Russia, altogether occupying three-fifths of the area of all Europe.

Asia.—Facing the open Indian Ocean stands the Himalayas; and in Central Asia the Altai Mountains face the great steppes and tundras of Northern Siberia, which extend northwards to the Arctic Ocean. Between these chains lie the plains of Mongolia and the Desert of Gobi.

Africa.—This continent is dominated by plateau forms, long continued denudation having truncated or altogether effaced the mountain-chains.

A high rim of land faces the Indian Ocean, and as a result the drainage of the interior is westward and northward, the Zambesi being the only river to break through to the Indian Ocean.

Australia.—The plateau form of Australia is even more conspicuous than that of Africa. A rim of mountains—the Australian Alps—borders the eastern side of the continent, as shown in fig. 229, and on the west lies the Great Western Plateau.

PART III.

CHAPTER XXXV.

ECONOMIC GEOLOGY.

Economic Geology is mainly concerned with the occurrence and genesis of ores and mineral deposits; with coal and mineral oil; building-stones and roofing-slates; flagstones and road-metal; limestones and cements; grindstones and whetstones; ornamental stones and marbles; clays for brick-making and pottery; sand for glass-making; soils; and with the supply of underground water for domestic, manufacturing, agricultural, and medicinal purposes.

Ores and Mineral Deposits.

Mineral deposits mostly occur as *veins* or *lodes* traversing rock-masses, or as *sheets*, *layers*, or *beds* interbedded with and forming part of rock-formations.

In regions which have suffered considerable denudation, the valuable contents of veins and mineral deposits may be concentrated in the sands, gravels, or other detritus laid down along the course of the streams and rivers, or on sea-beaches. Such deposits are called *alluvial* or *detrital*, and are obviously of secondary origin.

Definitions.—A *vein* or *lode* may be defined as a more or less continuous sheet-like body of ore enclosed within rocky walls. It may be horizontal or vertical, or inclined at any angle.

The term *vein* is frequently restricted to designate the simple sheets of relatively small dimensions possessing well-defined walls; while the term *lode* is more often applied to the larger ore-bodies, or to zones or bands of mineralised rock that contain strings, bunches, or ramifying veins or veinlets of valuable ore.

An *ore* may be defined as any natural metallic or non-metallic substance that can be turned to profitable account by metallurgical manipulation. It therefore excludes such substances as slate, chalk, clay, and building-stones.

A *lens* or *lenticel* of ore is one shaped like a biconvex or plano-convex lens. Such deposits taper out to small dimensions in all directions, or *peter* out altogether.

Mineral Deposits Morphologically Considered.

Classification.—Mineral deposits are found in many different forms and under many varying conditions. Moreover, they present a great diversity of origin. Hence they may be considered *morphologically*, that is, according to their outward form, or *genetically*, according to their origin. Of these, outward form and mode of occurrence offer the most convenient starting place for the elementary investigation.

The *morphological* classification, based on outward form and mode of occurrence, but entirely independent of age or mineral character, is as follows :—

Class I.—Superficial mineral deposits.
Class II.—Stratified mineral deposits.
Class III.—Unstratified mineral deposits.

For convenience of study and description these classes are subdivided into groups or sub-classes :—

I.—SUPERFICIAL DEPOSITS.

(*a*) *Detrital*—Forming or occurring in alluvial drifts.
(*b*) *Massive*—Forming superficial layers and sheets.

II.—STRATIFIED DEPOSITS.

(*a*) *Constituting beds*—Forming members of a stratified formation.
(*b*) *Disseminated through a bed.*

III.—UNSTRATIFIED DEPOSITS.

(*a*) *Deposits of volcanic origin.*
(*b*) *Stockwork deposits.*
(*c*) *Contact and replacement deposits.*
(*d*) *Fahlbands.*
(*e*) *Impregnations.*
(*f*) *Segregated veins.*
(*g*) *Gash-veins.*
(*h*) *Fissure-veins.*

CLASS I.

Superficial Deposits.

(*a*) **Detrital.**—Alluvial or *placer* deposits, as they are usually called, embrace detrital deposits of all kinds, whether beach sands, river gravels, lacustrine gravels, or glacial drifts, containing particles of gold, platinum, tin-ore, iron ores, emeralds, rubies, diamonds, or other precious stones.

The alluvial deposits may be of recent date or of great antiquity. They may exist as sands and gravels in the bed or bank of a stream; or form terraces ranging in age from the Pleistocene to almost recent times; or occur as so-called *deep-leads* which are merely river-drifts of Pliocene and later date covered over and protected by sheets of basaltic lava; or occur as consolidated gravels or conglomerates interbedded with rocks ranging in age from the Silurian to the late Cainozoic.

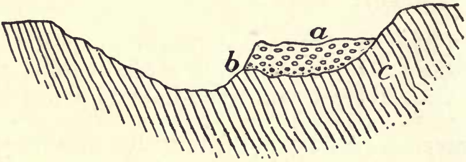

FIG. 230.—Section of gold-bearing river-terrace.
(*a*) Terrace gravels. (*b*) Pay-wash. (*c*) Slate bed-rock.

The most widely distributed and valuable of alluvial deposits are those of gold. The alluvial gold originated from the weathering and denudation of country containing gold-bearing veins during countless centuries, followed by the concentration of the liberated particles and nuggets of gold in the gravelly bed of the streams and rivers by a process of natural sluicing.

The gold, owing to its great specific gravity, gravitates toward the bottom of the drifts and usually lodges on or near the bed-rock. The crevices in the bed-rock, which is frequently slate, sandstone, or mica-schist, offer a convenient and safe lodgment for the travelling particles of gold.

The portion of the gravel drift which contains the gold is called the *pay-wash*.

The pay-wash usually lies on the bed-rock, or *true-bottom* or *reef-bottom* as it is called, but in thick accumulations of river-drift, two, three, or more layers of pay-wash may exist, each resting on a bed of clay or distinctive bed of gravel, which is called a *false-bottom*.

The most valuable gold-bearing drifts occur in California, the State of Victoria in Australia, and New Zealand.

Deep-leads of great value occur in California, and at Ballarat in Victoria, underlying thick sheets of basaltic lava of late Tertiary date.

Tin-bearing gravels of great extent and value occur in Malaysia, which produces the bulk of the world's annual supply of tin-ore.

The platinum-bearing gravels on the eastern slopes of the Ural Mountains produce 90 per cent. of the platinum of commerce.

Diamond-bearing gravels occur on the banks and bed of the Vaal River in South Africa, and ruby placers have been worked for centuries in Burma, and for many years in Brazil.

(*b*) **Massive.**—Deposits of this kind occur in superficial sheets, layers, or masses frequently covered with soil, clay, or other recent accumulations. They include deposits of bog iron-ore, laterite, rock-salt, sulphur, and rock-phosphate.

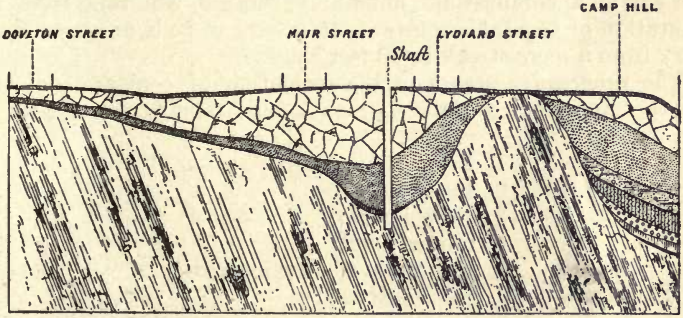

Fig. 231.—Showing deep-lead underlying sheet of basalt, Ballarat Goldfield, Victoria.

Bog Iron-Ore is an impure hydrated peroxide of iron which frequently forms on the bottom of swamps and shallow lagoons.

Laterite is mainly composed of alumina and iron oxide, with sometimes manganese and titanium. When the surface of a flow of basaltic or other basic lava is exposed to the weathering action of the atmosphere in a warm moist climate, the carbonic acid in the air, in conjunction with water, attacks the felspars and removes the silica, lime, magnesium, potash, and soda in solution. The alumina and iron are left behind as a reddish-brown or brick-red sheet of earthy ironstone.

The brick-red layers of lateritic clay frequently seen in ancient volcanic regions intercalated among lava-flows and beds of ash are surfaces of lavas that have become weathered and decomposed during periods of cessation from volcanic activity.

Superficial layers of rock-salt occur in the dried-up swamps and lagoons in the arid regions of Asia, North America, and Australia. Deposits of sulphur occur in volcanic regions, and rock-phosphates are often found on the chemically eroded surfaces of limestones, where they have accumulated by a process of secondary concentration.

Class II.

Stratified Deposits.

(*a*) **Constituting Beds or Strata.**—The useful minerals which occur in beds or as members of a stratified formation are coal, oil-shale, iron-ore, and rock-salt.

Coal is a combustible mineral substance resulting from the alteration of vegetable matter. It occurs in beds or *seams* which vary from a mere streak to 90 feet thick.

The progressive stages in the formation of coal are indicated by the numerous varieties which occur, ranging from peat to anthracite:—

1. Peat.
2. Lignite.
3. Brown coal.
4. Cannel coal.
5. Bituminous or coking coal.
6. Semi-anthracite.
7. Anthracite.

The principal coal-bearing formations are the Carboniferous in Britain, Belgium, and North America; Permo-Carboniferous in New South Wales and India; and Eocene and Miocene in New Zealand.

Some brown coals are Upper Cretaceous, as in New Zealand, but in most countries they are Lower and Middle Cainozoic, as in Texas, South Hungary, North Germany, and New Zealand.

Lignites are mostly of Pliocene and Pleistocene age.

Coal-seams may be horizontal, or inclined, folded, bent, or overturned, according to the amount of disturbance suffered by the strata in which they are enclosed.

Oil-Shales occur in Carboniferous rocks in the Lothians of Scotland, Permo-Carboniferous of New South Wales, and Lower Cainozoic of New Zealand. Oil is obtained from them by distillation.

Natural Mineral Oil is obtained by boring in California, Texas, Ohio, Pennsylvania, Baku, Burma, Borneo, and other regions. Its origin is supposed by some writers to be igneous or inorganic, but

To face page 509.] [PLATE LXX.

the bulk of the evidence seems to favour the view that it is organic, resulting from the destructive distillation of animal and vegetable organisms buried in marine and lacustrine sediments.

The oil is expelled as gases from the muds, shales, and calcareous deposits in which the organisms were buried, and is condensed into heavy oil in the overlying porous sandstones or strata, where it accumulates under great pressure.

When the impervious strata overlying the porous sandstones are penetrated by bore-holes, the oil and gases rise to the surface.

Beds of *rock-salt* occur in many geological formations. Those of the Salt Range in the Punjab are Cambrian; and of Cheshire, Triassic; while the famous salt-deposits of Wieliczka in Polish Austria are Miocene.

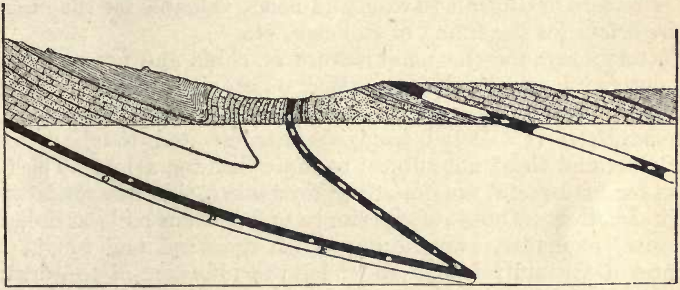

FIG. 232.—Section across Shenandoah Basin, Pennsylvania anthracite region, showing an overturned seam of coal.

Other Bedded Deposits.—Among other bedded deposits of great value to man are Building-stones, Roofing-slates, Limestones, Flagstones, and Road-metals, Clays, and Ornamental stones.

The most valuable *Building-stones* are granite, sandstones, and limestones. Granite is hard, durable, and takes a fine polish. The siliceous sandstones are also hard and durable, while the softer calcareous sandstones or *freestones* are free-cutting, and hence of special value for the construction of front-walls and ornamental parts of buildings. The oolitic limestones of England and Continental Europe, and the magnesian limestones common in many parts of the globe, are valuable for all kinds of buildings.

The best *Roofing-slates* are obtained from fine, even-grained, muddy sediments in which slaty-cleavage has been well developed. They are found in all the older Palæozoic formations in many parts of the globe. The Welsh roofing-slates are the best in Britain, and are seldom equalled in other regions.

Limestones containing 80 per cent. or more of carbonate of lime are valuable for burning into lime for agricultural purposes, and for the making of cement and mortar. Such limestones are found in almost all the rock-formations from the Cambrian to the late Cainozoic. In Britain the Wenlock or Dudley Limestone, the Carboniferous and Oolitic Limestones, and the Chalk are specially valuable. The impure, earthy limestones of the Jurassic and Cretaceous, so abundant in England, France, United States, and New Zealand, when calcined and pulverised, form natural *hydraulic cements* of great value. Portland cement is extensively manufactured from lime mixed with a suitable quantity of sea-mud or marl.

Common *Clays* are everywhere used for brick- and tile-making. The clays of the Coal-Measures, from which the lime, soda, and potash have been exhausted by the growth of the coal-vegetation, are *refractory* or difficult to fuse, and hence valuable for the making of *fire-bricks* for the lining of furnaces, etc.

Pottery clays for the manufacture of china and porcelain ware are derived from the disintegration of granitic rocks. Cornwall and Devon have long been noted for their production of *Kaolin.*

Road-Metal is selected from the hardest and toughest rocks available, and those not subject to rapid disintegration. The best rocks for road-metal are granites, greywackes, siliceous sandstones, and quartzites. These are superior to such igneous rocks as dolerite, andesite, phonolite, and diorite, which are hard and tough, but disintegrate rapidly into mud under the influence of the organic acids liberated from road-refuse.

Flagstones are usually sandstones, schists, or limestones that can be readily split into thick flags. The famous calcareous flagstones of Caithness, of Old Red Sandstone age, are exported to all parts of the globe. Flagstones of slate, limestone, gneiss, and quartz-schist are extensively used, but natural stones are being largely replaced by artificial slabs of concrete and other stony mixtures.

Ornamental Stones are usually hewn from granites, gabbros, marbles, and serpentine. The grey granite of Cornwall, the grey and pink granites of Aberdeenshire, the Carboniferous and Devonian Limestones of Europe and America are much used as ornamental stones. The statuary marbles of Carrara, in the Trias of the Apennines, have long been celebrated for their pure colour and even texture.

Glass-making Sands are plentiful in the older Cainozoic formations of the United States, England, Brazil, and New Zealand at the base of the brown Coal-Measures.

Grindstones and *Millstones* are fashioned from gritstones and siliceous sandstones like the Millstone Grits of England.

Whetstones are often made from fine-grained lavas and siliceous slates or hornstones.

(*b*) **Disseminated through a Bed.**—Certain beds or strata of sedimentary formations are sometimes impregnated with valuable ores or minerals, the origin of which is uncertain. The metals were either introduced contemporaneously with the deposition of the sediments in which they occur, or after the consolidation of the sediments.

Among the most notable examples of this class of deposit are the famous gold-bearing *banket-reefs* of the Rand, in the Transvaal, which are merely beds of quartzose conglomerate impregnated with gold and pyrites ; the celebrated copper-bearing shales of Mansfeld, in Prussian Saxony, which have been worked for eight hundred years ; the rich copper-bearing conglomerates of Lake Superior ; the Silver Sandstones of Utah ; and the Lead Sandstones of Commern, in Rhenish Prussia.

Class III.

Unstratified Deposits.

(*a*) **Deposits of Volcanic Origin.**—These include deposits of sulphur and borax, which accumulate in and around fumaroles in the form of sublimates. The fumarolic sulphur of Vesuvius, Etna, and volcanic regions of Japan and New Zealand is of great economic value. The steam fumaroles of Pisa, in Italy, yield a large annual output of boric acid.

(*b*) **Stockwork Deposit.**—A Stockwork is a rock-mass traversed by numerous small veins that mutually intersect one another, but are too small to be worked separately. The valuable ore may be tin, gold, or any metal of economic importance. With such deposits it is necessary to quarry the whole of the rock-mass in order to extract the valuable mineral, hence the name *Stockwork*, which refers to the quarry-system of mining.

The celebrated gold-bearing ore-bodies at the Treadwell Mines in Alaska are good examples of this class of deposit.

(*c*) **Contact and Replacement Deposits.**—A Contact Deposit is one which occurs at or near the contact of a sedimentary rock and an intrusive mass or dyke.

Valuable deposits of iron-ores, and of copper, lead, and zinc sulphates are frequently found in the vicinity of intrusive dykes.

The famous copper-bearing pyritic ore-bodies at Rio Tinto, in Spain, are typical Contact Deposits.

(*d*) **Fahlbands.**—These are bands or zones of crystalline metamorphic rocks so highly impregnated with ore as to be of commercial value. The silver-bearing Fahlbands (grey beds) of Norway are among the best known examples. They follow the strike and dip of the strata by which they are bounded. The thickness may vary from a few inches to hundreds of feet.

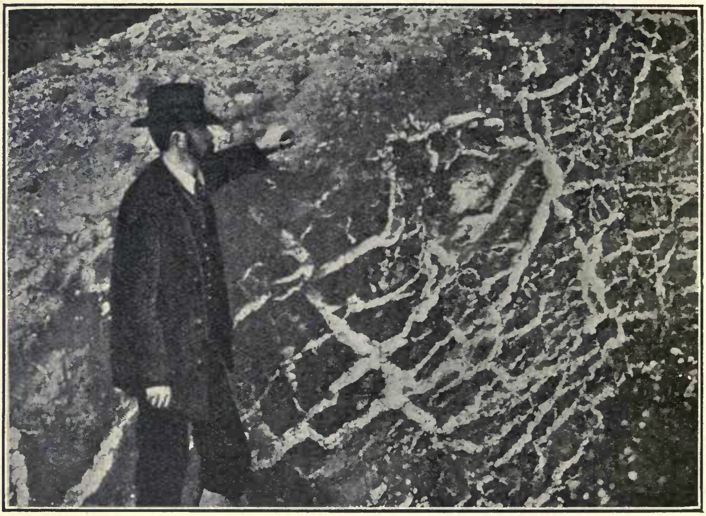

Fig. 233.—Showing stockwork of magnesite veins, *U.S. Geol. Survey*.

Fahlbands are related to bed-impregnation, and probably owe their origin to aqueous and gaseous emanations expelled from a cooling intrusive magma.

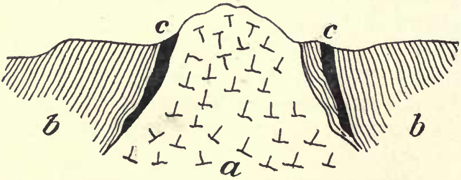

Fig. 234.—Showing section of contact deposits.
(*a*) Granite. (*b*) Slate. (*c*) Contact deposit.

(*e*) **Impregnations.**—It has sometimes happened that when a rock has been fissured, a portion of the rock on one or both walls has become impregnated with some metallic substance, disseminated as grains, bunches, or nests throughout the mass in the vicinity of the fissure.

Such an occurrence is called an *Impregnation*, implying that the mineral has been introduced as a secondary product by mineralised waters, superheated steam, or gases.

The term "impregnation" refers to the genesis rather than the form of the ore-body. Genetically the majority of Stockworks, Contact Deposits, and Fahlbands may be regarded as impregnations, as well as such bedded deposits as the so-called Banket-reefs of the Rand, the copper-deposits of Mansfeld, the Silver Sandstones of Utah, etc.

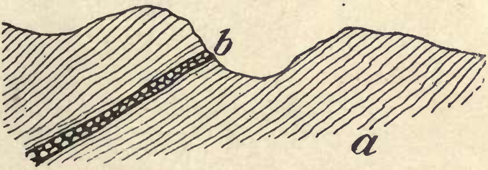

FIG. 235.—Showing fahlband at Dusky Sound, New Zealand.
(*a*) Mica-schist. (*b*) Fahlband of pyrrholite, etc.

Granite and other acid igneous rocks are sometimes impregnated with tin-ore, and such tin-impregnations may be regarded as typical of this class of deposits. Among the most famous is the Mount Bischoff tin-deposit in Tasmania.

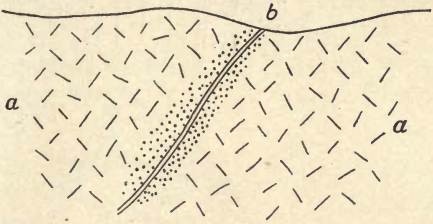

FIG. 236.—Tin-impregnation.
(*a*) Granite. (*b*) Tin-ore.

(*f*) **Segregated Veins.**—These are only found in sedimentary rocks which have been sharply folded, whereby fissures or cavities have been formed in the bent portions more or less parallel with the bedding planes. That is, Segregated Veins mostly occur along the crest of anticlinal axes, and sometimes along the axes of synclines.

The best example of Segregated-Veins are *Saddle-Reefs*, which are typically developed at Bendigo, in the State of Victoria. These

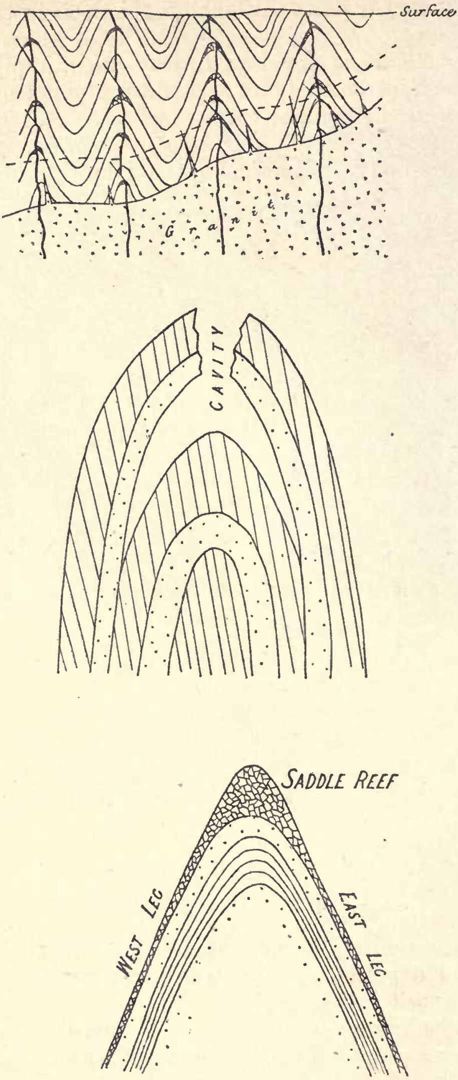

Fig. 237.—Sections showing formation of saddle-reefs. (After E. J. Dunn.)

gold-bearing ore-bodies consist of arch-like masses of quartz that conform to the bedding planes and taper out going downward.

In what are called *Inverted Saddle-Reefs* the ore-bodies occur in the troughs of the folds. Good examples of Inverted Saddle-Reefs are found at Mount Boppy, in New South Wales.

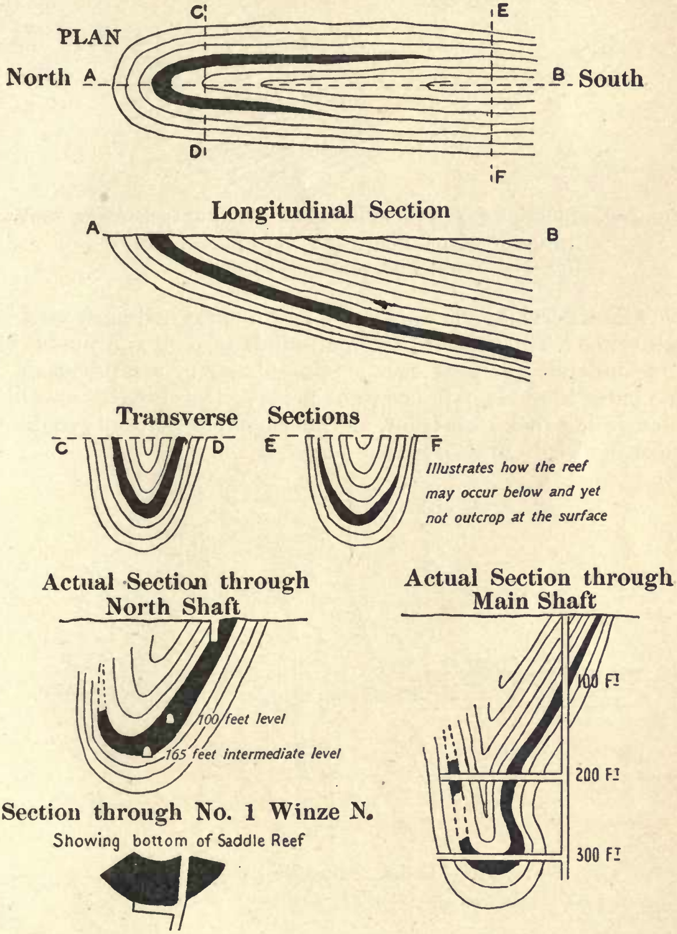

FIG. 238.—Sections showing structure of inverted saddle-reefs. (After Jaquet.)

(*g*) **Gash-Veins.**—These are metalliferous deposits occupying lenticular or lens-shaped cavities or gashes in limestones. They generally occur at the intersection of cross-joints where cavities have been formed by the action of water, and simultaneously or subsequently filled with metallic ores. The ores that usually occur in this form are those of lead and zinc.

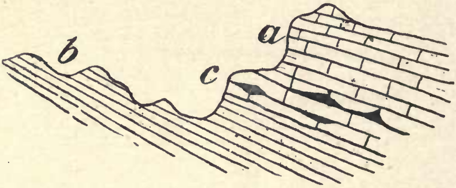

FIG. 239.—Showing gash-vein in limestone at Wangapeka, New Zealand.
(*a*) Silurian limestone. (*b*) Silurian slate.
(*c*) Gash-veins, with galena and blende.

(*h*) **Fissure-Veins.**—These are the best defined and most persistent of all veins. They pass through all kinds of rock and pursue their course independently of the bedding planes or stratification. In some parts they may chance to coincide with the strike and dip of the enclosing rock-formation, and in such places they are difficult to distinguish from Segregated Veins.

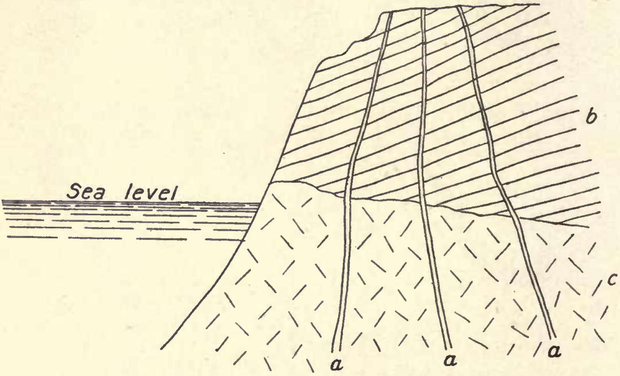

FIG. 240.—Lodes of Botallic Mine, Cornwall.
(*a*) Lodes. (*b*) Slaty shales. (*c*) Granite.

All veins that crop out at the surface have been more or less truncated by denudation.

The mineral contents of Fissure-Veins were in most cases deposited by ascending aqueous solutions that were probably genetically connected with some deep-seated igneous intrusion.

The different minerals composing the vein-filling are frequently arranged in layers parallel with the walls. When the layers are made up of crystalline aggregates, the crystals are often arranged with the longer axis at right angles to the plane of the walls, thereby presenting the appearance called *comb-structure.*

The tin-lodes of Cornwall are typical examples of Fissure-Veins.

Filling of Cavities and Veins.—The vein-filling or *gangue* of lodes, in which the valuable metal or ore is embedded, is in most cases

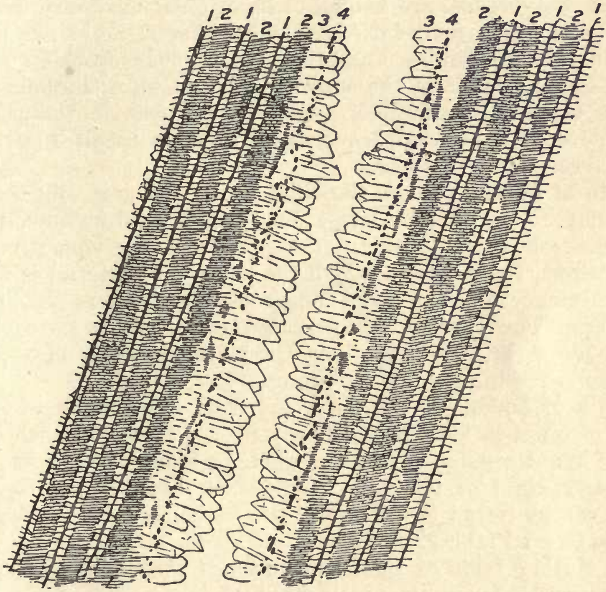

FIG. 241.—Showing comb-structure of lode-matter. Section showing arrangement of ore in vein.

1, Quartz, with galena and zinc blende. 3, Vug quartz.
2, Country-rock. 4, Iron pyrite disseminated through quartz.

quartz, which may be crystallised or chalcedonic. Ores of lead and zinc are, however, usually enclosed in a gangue of fluor-spar or calcite.

Origin of Vein-Cavities.—The solutions which deposited the vein-matter and its valuable contents either found the cavities and fissures awaiting them, or they formed their own channels by a process of slow progressive dissolution and replacement of the wall-rock along pre-existing cracks or fractures.

The pre-existing cavities and fractures were mechanically formed in sedimentary rocks by folding, or by igneous intrusions; and in eruptive rocks by contraction arising from cooling.

Where the fracturing of the rock has been produced by igneous intrusions, these frequently provide the mineralised vapours and solutions that corrode the shattered rock and fill the fissures with mineral matter.

Ore-bodies are often formed along joint- and fault-planes, and at the intersections of joints, simple fractures, and faults.

Some rock-fissures are known to be of great antiquity from the presence of fossils in the material filling them. Dyke-like masses of sandstone containing Cambrian brachiopods occur in granite in the Aland Islands at the entrance of the Gulf of Finland; and narrow veins of fossiliferous sandstone are seen in the sea-cliffs at Oamaru, New Zealand, traversing a sheet of basalt intercalated with Lower Miocene strata.

Depth of Lodes.—Where the lodes occupy fissures confined to a particular rock, or rock-formation, like the propylite-veins of Cripple Creek and Hauraki, or the gash-veins so frequently found in limestone, the depth to which the lodes may descend is limited by the thickness of the containing rock. But where the original fissures pass down through the crust without regard to the character or number of the rock-formations, the lodes may descend to depths far beyond the limits of deep mining.

Length of Lodes.—Lodes may vary from a few hundred feet to scores of miles in length. In Cornwall, the average length of the lodes is about a mile; in Saxony, three or four miles; in the Harz Mountains, eight or ten miles. The Asch Lode in the Bavarian Forest can be traced for 25 miles; the Bohemian Pfahl, 34 miles; and the Great Pfahl, 92 miles.

The Mother Lode of California extends through five counties, being traceable for a distance of 70 miles.

Width of Lodes.—Lodes may vary in width both along their course and in depth. The same lode may vary from a mere clay parting to hundreds of feet in width. The celebrated Comstock Lode, Nevada, varies from 20 to 300 feet wide. The Great Pfahl, the most colossal quartz-lode in the globe, maintains an average width of 100 feet, but in places widens out to 370 feet.

Most great lodes occupy fault-fractures. The three gigantic lodes of the Bavarian Forest are regarded by Suess as the greatest monuments of linear dislocation in Europe.

Age of Vein-Filling.—In the case of veins and lodes traversing sedimentary and metamorphic rocks, it is natural to suppose that the formation of the ore-bodies would follow the periods of great orogenic movements, two of which are specially notable in geological history, namely, the late Carboniferous and the Middle

Cainozoic. Both were characterised by extraordinary volcanic activity and igneous intrusion.

The uplift and intense folding of great segments of the earth's crust cause the formation of powerful fractures, which afterwards became channels for the circulation of mineral-bearing waters.

If a lode traverses a pile of strata ranging in age from the Silurian to the Jurassic, it is obvious that the age of the lode-matter must be post-Jurassic. And if the Jurassic strata are overlain by an Eocene formation which the lode does not penetrate, then we know that the age of the lode is post-Jurassic and pre-Eocene, that is, Cretaceous.

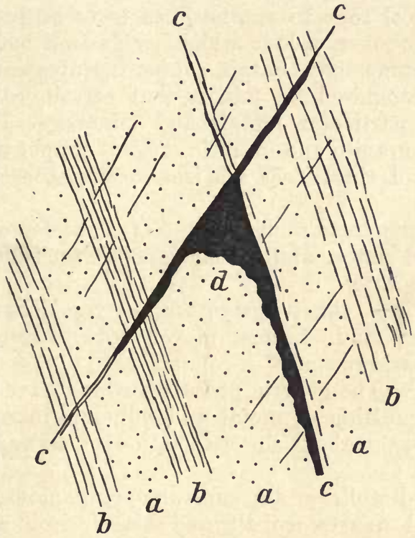

Fig. 242.—Showing formation of ore-body at intersection of joint planes, Bendigo Goldfield, Victoria. (After T. A. Rickard.)

In the Hauraki, Cripple Creek, Tonopah, Goldfield, and some Transylvanian mining areas, the gold-bearing veins are confined to andesitic lavas and tuffs of Middle Tertiary age. The veins occupy contraction cracks, and their filling must have taken place in late Tertiary times. Such veins are called *Propylite* veins, to distinguish them from *Tectonic* veins, which occupy cracks and cavities formed by crustal folding. *Fissure-veins* are profound fractures passing from one formation to another; and *Saddle-reefs* are typical examples of the tectonic type of ore-body.

Distribution of Valuable Contents in Lodes.—The matrix or gangue of most metalliferous lodes is quartz, but it is seldom that the valuable ore is equally distributed throughout the whole mass of vein-stone. Usually it occurs in isolated *bunches*, *nests*, *patches*, *pockets*, or *pipes*, to which the general term *pay-shoot* is frequently applied.

The pay-shoot or commercially valuable ore may occur on the *foot-wall*, *hanging-wall*, or middle of a lode, the remaining portion of which may be barren or too lean to be profitable. Or it may occupy the full width of that portion of the lode in which it occurs.

Influence of Country-Rock.—Frequently a lode, when it passes from one kind of rock to another, ceases to be profitable, or the converse. Moreover, a lode which yields lead and zinc where it traverses limestone, may contain copper in slates and tin in granite.

It is well recognised by miners that certain rocks favour the occurrence of particular metals and minerals. Thus tin has a preference for granite and granitic rocks; copper and chrome for serpentine; lead, zinc, silver, and iron for limestones and calcareous rocks.

Among sedimentary rocks gold has a preference for ancient sandstones and slates, and among igneous rocks for andesites of older Cainozoic date.

In a general way tin, tungsten ores, and gold have a preference for acid rocks; and chrome, nickel, cobalt, iron, copper, and platinum for basic rocks.

Paragenesis.[1]—The genetic processes which have led to the formation or deposition of metal and minerals in ore-bodies have frequently brought about the association of certain minerals with one another.

Thus tin and wolfram are constant companions, also lead and zinc, gold and quartz, cobalt and nickel, iron and copper (as sulphides), chrome and serpentine.

Secondary Enrichment of Veins.—Sulphide ore-bodies, which crop out at the surface in non-glaciated regions, usually consist of two distinct portions, namely, the *oxidised zone* or *zone of weathering*, and the *unoxidised zone*, which generally lies below water-level.

The oxidation of the upper portion of the lode is due to the action of rain-water, usually called *meteoric* water. The depth to which the alteration may extend is dependent on local topographical conditions and may vary from a few feet to 200 or 300 feet.

Mining operations have shown that most oxidised sulphide ore-bodies contain abnormally rich ore in the oxidised zone, frequently in the lower portion of it. This rich ore is supposed to arise from the migration of the valuable metallic contents from the higher portion of the vein to the lower portion through the agency

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[1] Gr. *para* = along side of, and *genesis* = birth.

of meteoric waters. In some cases the processes of dissolution, migration, and deposition of the ore may have taken place over and over again, each cycle resulting in a greater concentration of the valuable portion of the ore.

Secondary enrichment may also arise through the removal of the worthless metals, thereby leaving the valuable ore in a purer form.

The metals held in solution by permeating waters may be deposited as secondary sulphides on the primary sulphides in the lower portion of the lode. This is conspicuous in the Mount Lyell and Rio Tinto sulphide ore-bodies.

The first operation in the process of secondary enrichment is the chemical weathering and oxidation of the sulphides in the zone of weathering. The surface waters, now charged with minerals in solution, descend through the body of the lode and deposit their valuable contents in a concentrated or purer form through chemical or electrolytic action.

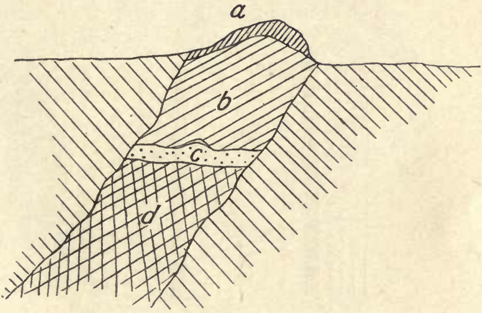

FIG. 242A.—Showing Zones of Oxidisation and Secondary Enrichment.

(*a*) Ironstone cap or *gossan*. (*b*) Zone of oxidised ore.
(*c*) Zone of Secondary Enrichment. (*d*) Primary sulphides.

Metasomatic Replacement.—Until lately it was the common belief that veins and all ore-bodies occupied pre-existing fissures and cavities in the country-rock. In recent years much stress has been placed on what is called *metasomatic replacement*, which is now regarded as an important process of lode-formation.

According to this hypothesis, it is surmised that the mineralised waters percolating through the rocks dissolve certain tracks or zones which they partially or completely replace with mineral matter and ores. In many cases the altered zone follows the track of a fissure, bedding plane, or fault; but the replacement may follow a particular band of rock without the aid of leading cracks or fissures.

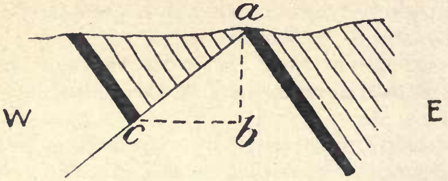

FIG. 244.—Showing displacements caused by strike-fault.
(*a-b*) Vertical displacement of throw. (*b-c*) Horizontal shift.

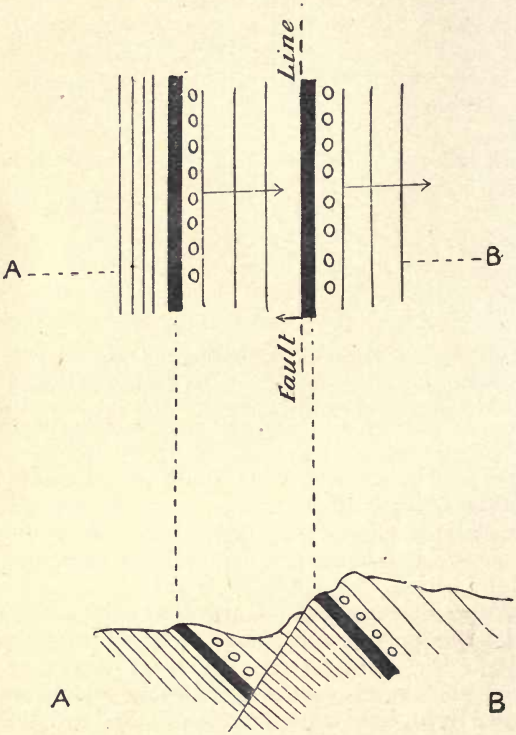

FIG. 245.—Showing repetition of coal-seam by strike-fault

Metasomatic replacement may take place among certain constituents of rock-masses, no matter how dense; and is common in

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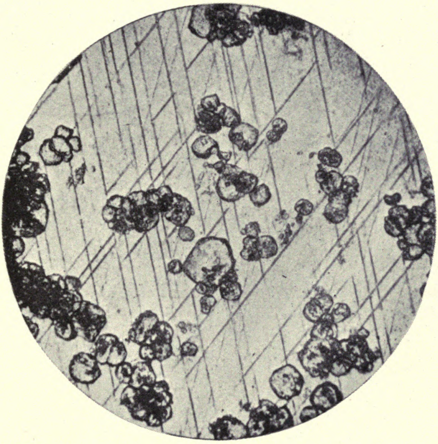

FIG. 243.—Showing iron and copper pyrites intergrown with garnets.

metamorphic rocks and all older igneous masses. A notable example is the alteration of andesites to propylite.

The interchange of constituents proceeds molecule by molecule until large bodies of rock along certain zones are altered to mineralised ore-bodies. It is related to *pseudomorphism*, in which a mineral is removed and replaced by another mineral.

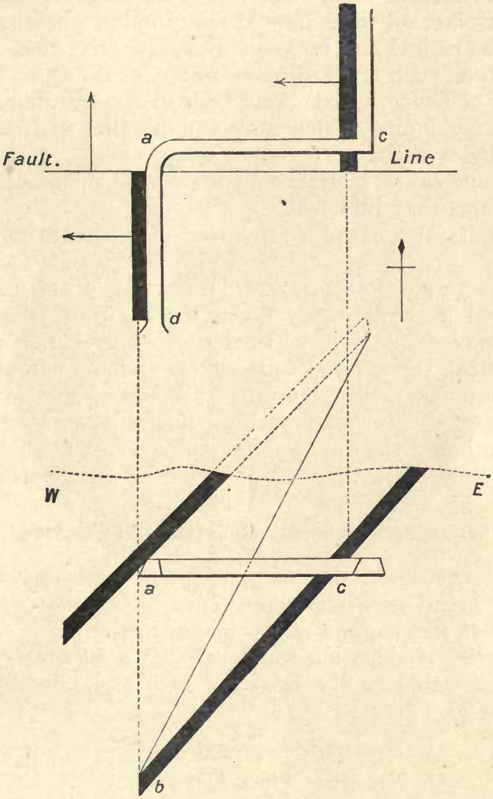

FIG. 246.—Showing effect of dip-fault.

There was always a difficulty in believing that such huge ore-bodies as the Broken Hill Lode in New South Wales or the Comstock Lode in Nevada occupied fissures which had remained open as gaping chasms until they became filled with mineral matter.

The symmetrical banding of the lode-matter on the opposite walls of many lodes and the comb-structure are conclusive evidence that some small fissures did remain as open channels during the deposition of the vein-filling. It is not improbable that in crustal areas in tensional stress the width of the cracks and fissures might continue to increase for a considerable time during the filling process.

Brecciated Lodes.—Wall-movements of considerable magnitude have taken place on the course of many lodes, whereby the gangue has become crushed and broken. Subsequently when re-cemented by infiltration, such crushed lode-matter is said to be brecciated.

Faulting of Lodes.—Lodes and bedded mineral deposits may be intersected by faults, which may run parallel with the strike or at right angles to it.

Strike-faults cause vertical and horizontal displacements of the veins or seams they intersect.

Strike-faults also cause a repetition of the seam or vein at the surface.

Dip-faults produce an *apparent* lateral displacement of the beds or veins which they cross. When the faulting takes place, the principal movement is a vertical one. Consequently, when the vein is vertical, the severed ends merely slide on one another.

The apparent *heave* or lateral displacement is produced by the denudation of the elevated portion causing the outcrop to recede in the direction of the dip as shown in figs. 95 and 96. The flatter the dip, the greater will be the apparent lateral displacement.[1]

Ores and Minerals Genetically Considered.

The constant association of ore-deposits and igneous rocks has led to the broad generalisation—*That ore-deposits are genetically connected with the eruption of igneous magmas.*

The genetic classification which satisfies most nearly our present knowledge relating to the origin of ores and minerals comprises four classes as follow:—

I. Magmatic Segregation.
II. Eruptive After-Actions:—
    (*a*) *Solfataric.*
    (*b*) *Fumarolic.*
    (*c*) *Contact metamorphic.*
    (*d*) *Regional metamorphic.*
III. Meteoric Waters:—
    (*a*) *Chemical.*
    (*b*) *Mechanical.*
IV. Organic.

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[1] The recovery of faulted lodes and coal-seams by graphic projection is fully described in Park's *Mining Geology*, Charles Griffin & Co., Limited.

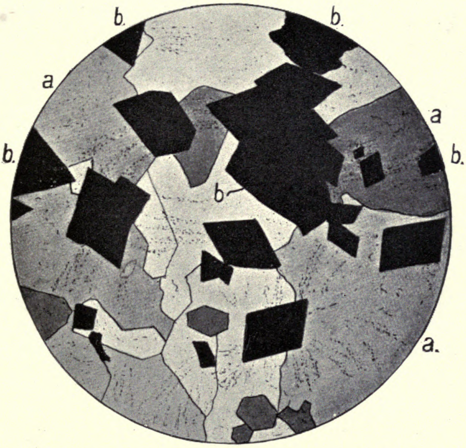

FIG. 247.—Showing structure of pyritic quartz in thin section, *U.S. Geol. Survey*. (After Lindgren.)

(*a*) Quartz. (*b*) Arseno-pyrite.

I. Magmatic Segregation.

This class includes all ores and minerals which occur as primary constituents of igneous rocks, resulting from direct segregation in the cooling magma.

The most important ores occurring as primary constituents of igneous rocks are :—

Chromite, found in serpentine and peridotite.
Copper and *nickel-iron*, in serpentine.
Platinum, in peridotite and other ultra-basic eruptives.
Magnetite and *titanite*, in basic and semi-basic eruptives.

II. Eruptive After-Actions.

The after-actions resulting from an igneous intrusion will commence at the moment of intrusion and continue with waning intensity until the magma has completely cooled.

Solfataric.—Volcanic eruptions are usually accompanied by the emission of enormous volumes of steam ; also hydrogen sulphide, sulphur dioxide, carbon dioxide, as well as compounds of chlorine, fluorine, and boron.

These gaseous and aqueous emanations come from the same source as the igneous magma, accompany the magma in its ascent, and may possibly be one of the contributing causes of the eruption.

In the expiring stages of volcanic activity in some regions, geysers, hot-springs, and fumaroles occur in the vicinity of the volcanic vents.

The geysers and hot springs deposit incrustations of silica on the walls or passages through which the waters flow. At the surface they cover large areas with successive layers of silica, which in time form circular mounds around the vent-holes.

The silica when first deposited is soft and gelatinous, but it soon becomes hard and assumes the chalcedonic form.

The siliceous sinters being deposited at Rotorua, in New Zealand, contain both gold and silver.

The gold-bearing chalcedonic and crypto-crystalline lodes at Waihi, in New Zealand, traversing andesites and dacites, are of solfataric origin, as also are the great umbrella-shaped lodes scattered throughout the same region. The gold-bearing lodes at Cripple Creek, Goldfield, and Telluride, which occur in older Tertiary andesites, etc., are also solfataric.

Fumarolic.—Deposits of sulphur and borax are formed by the aqueous and gaseous emanations in the waning stages of volcanic activity in almost all volcanic regions where eruptions have taken place in late Tertiary and Recent times.

The sulphur deposits of Italy, Sicily, Japan, and New Zealand may be taken as typical examples of the fumarolic class of mineral deposits.

Contact Metamorphic Deposits.—An intrusive plutonic magma tends to effect considerable changes in the rocks with which it comes in contact. The greater the mass of the intrusion, the slower will be the rate of cooling; and the slower the rate of cooling, the longer will the adjacent rocks be heated.

The rate of cooling will be dependent on the mass of the intrusion, its distance from the surface, and the relative thermal conductivity of the covering and enclosing rocks.

The changes effected by the intrusive magma will be mainly mechanical, thermal, and chemical.

The intruded rocks will be compressed, bent, and more or less shattered and fissured in the neighbourhood of the intrusion.

The magma will part with its heat by slow radiation into the adjacent rocks.

The steam and gases occluded in the cooling magma, together with the steam generated from the water contained in the rocks in contact with the magma, will pass into and permeate the surrounding rocks, and thereby cause a molecular rearrangement of the constituent minerals, resulting in what is called *contact metamorphism.*

As the igneous magma and the intruded sedimentaries cool, they will contract in mass; and cracks, fissures, and cavities will be developed in them along the line of contact. These fissures and cavities will form channels for the circulation of the mineralised underground solfataric waters, which will in time fill them with mineral matter.

Above a temperature of 365° C. and a pressure of 200 atmospheres, water and all the more or less volatile compounds will exist as gases. These mineral-laden gases, being under enormous pressure, will permeate the shattered intruded rocks in all directions; and when their temperature falls, will condense and deposit their load of metals and mineral in every crack and crevice to which they are able to penetrate.

In this way rocks may become impregnated with ores near the line of contact, and in some cases ore-bodies may be formed at points a considerable distance from the intruding magma.

As the cooling proceeds, the least soluble substances, which are obviously the last to be dissolved, will be the first to be deposited; and as the temperature and pressure continue to diminish, the remaining metals and minerals will be deposited in the inverse order of their solubility.

It is obvious that the later stage of eruptive after-actions will represent, in a modified form, the waning effects of solfataric action. The deep-seated conditions with the greater pressure and temperature will also accelerate the action of metasomatic processes, whereby lodes may be formed in the zone of contact of metamorphism.

It is almost certain that the formation of contact-deposits, fissure-veins, and rock-impregnation may be traced to the same genetic causes, the actual form assumed by the ore-body being merely the result of some local geological condition.

Contact-deposits frequently lie along the boundary-line between the eruptive and the country-rock; also at variable distances from the eruptive, but never outside the zone of metamorphism.

The metallic ores which are the most common in contact-deposits are sulphides of copper, iron, lead, and zinc, also magnetite and specular iron. Typical pyritic contact-deposits are those of Rio Tinto and Tharsis in Spain, Mount Lyell in Tasmania, and Broken Hill in New South Wales.

Among the minerals developed in rocks that have been intruded by igneous dykes or introduced by vagrant-emanations from the intruding magma are garnet, vesuvianite, scapolite, wollastonite, augite, biotite, hornblende, chiastolite, etc.

Regional Metamorphic Deposits.—To this group belong the massive deposits of magnetite and specular iron that occur in crystalline metamorphic rocks of older Palæozoic age. The origin of the iron is uncertain. It probably existed in the original sediments and became concentrated and rearranged under the influence of heat, pressure, and underground solutions. The concentration of the iron and the metamorphism of the containing rocks are no doubt traceable to the same causes.

The valuable bodies of magnetite in Sweden and the greater masses of specular iron and magnetite in Michigan are notable examples of regional metamorphic ores.

Massive aggregates of magnetite and specular iron are common in chlorite-schist and mica-schist in all parts of the globe.

III. Meteoric Waters.

Chemical.—This group includes deposits of salt, borax, nitre, bog-iron ore, and some deposits of gypsum, rock-phosphate, and manganese.

Mechanical.—This embraces all sedimentary rocks and their contents; also alluvial drifts containing gold, platinum, tin, gems, etc.; likewise marine sands and gravels containing gold or other valuable metals, etc.

IV. Organic.

Vegetable.—This group includes all varieties of mineral fuel ranging from peat to anthracite; also graphite, oil-shale, mineral oils, natural gases, and infusorial earth.[1]

The ultimate source of carbon is undoubtedly magmatic, but the immediate source of most carbon compounds is organic.

Animal.—This subdivision includes limestones, coprolitic phosphates, infusorial earths, and some mineral oils.

Theories of Vein-Formation.

The two theories which receive the most support are:—

1. The Ascensional or Eruptive Processes Theory.
2. Lateral Secretion Theory.

Ascensional Theory.—According to this view, all ore-bodies and ore-veins owe their origin directly or indirectly to the intrusion of igneous magmas. The intrusive shatters the rocks and provides the metals which it brings up from the barysphere. The metals are expelled from the cooling magma in the form of highly-heated vapours which are deposited in the cracks and fissures in the neighbouring rocks. Moreover, the steam condenses and carries the metals upward through cracks and fissures which eventually become filled with mineral matter, thereby forming mineral veins. The alteration and replacement of the country-rock is also accelerated by the steam, gases, and heated waters emanating from the cooling igneous magma.

The almost constant association of ore-bodies and igneous intrusions gives powerful support to the Ascensional theory, which is now more favoured by mining geologists than any other.

Lateral Secretion Theory.—According to this view, it is assumed that meteoric waters percolating through the rocks, by the aid of carbonic acid and alkalies, dissolve out certain constituents, which are afterwards deposited in cracks, fissures, and cavities, thereby forming veins and ore-bodies.

In support of this view it is asserted that sedimentary and igneous rocks alike contain all the constituents formed in veins which are merely regarded as local concentrations.

It is well known that cracks in limestones soon become filled with calcite deposited by water slowly percolating through the body of the rock. Similarly, cracks and tension-rents in sandstones and igneous rocks become filled with quartz, calcite, pyrite, or

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[1] Most infusorial earths (so-called) consist of diatoms, that is, of plants; some consist of polycystines which are animal; they do not contain infusoria.

other minerals, all of them obviously local concentrations of mineral matter derived from the surrounding rocks.

The frequent association of igneous intrusions and ore-bodies is admitted by the supporters of the Lateral Secretion theory; but they contend that the gases and steam emanating from the magma merely accelerate and supplement the action of the meteoric waters in the concentration of the metals which previously existed in the intruded rocks as primary constituents.

Summary.—The Lateral Secretion theory does not satisfactorily explain the formation of the large pyritic replacement ore-bodies; hence at present the Ascensional theory receives the most support. At the same time it is acknowledged that the filling of cracks, fissures, and cavities with mineral matter is usually the work of meteoric waters, as also is the weathering and oxidation of the outcrops of lodes and secondary enrichment.

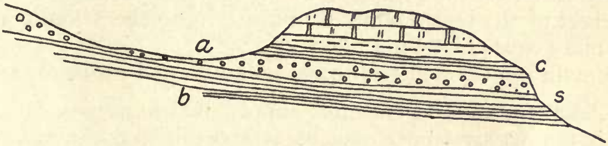

FIG. 248.—Showing natural spring.

(*a*) Porous stratum.
(*b*) Lower impervious confining bed.
(*c*) Upper impervious confining bed.
(*s*) Natural spring.

The processes of lateral secretion by meteoric waters may therefore be regarded as supplementary to the work of the ascending magmatic waters and gases.

WATER SUPPLY.

Water for domestic, manufacturing, and irrigation purposes may be obtained from rivers, lakes, natural springs, and artificial wells. Medicinal waters are usually derived from natural and artificial springs.

Natural Springs.—The requirements of a natural spring are:—

(1) A constant supply of water.
(2) A porous or permeable water-bearing stratum.
(3) Confining beds below and above the water-bearing stratum.
(4) A natural outlet at some point below the inlet or fountain-head.

When rain-water falls on a porous or pervious stratum, it will travel downwards until it reaches an impervious stratum or unfissured rock, along the plane of which it will travel until it reaches the surface, where it will form a natural spring. Obviously such a spring can only be formed where the porous water-bearing stratum crops out at the surface at a lower level than the fountain-head, as in a gorge, sea-cliff, hill-slope, or artificial cutting.

A discussion of what forms a porous stratum and adequate confining beds below and above the porous stratum will be found under the heading *Artesian Wells.*

Artesian Wells.

When underground water existing under hydraulic pressure is tapped by a well or bore-hole, it forms what is called an *artesian well.* The pressure may or may not be sufficient to cause the water to overflow at the surface.

The principle underlying the flow of artesian wells is based on the physical law that imprisoned water always tends to rise to the height of the inlet or fountain-head. In other words, gravity is the main cause of artesian flow.

The main requirements for an artesian flow of water are :—

(1) An adequate and constant supply of water.
(2) A porous stratum to act as a reservoir and channel for the underground flow.
(3) A confining stratum below and above the porous stratum or water-bearing bed.
(4) Absence of an outlet for the water at a lower level than the fountain-head.

Porous Stratum.—The ideal water-bearing stratum is a bed of sand, gravel, or porous sandstone ; but any rock that is crushed or jointed, or possesses distinct bedding planes, pores, vesicles, cracks, openings, or passages of any kind whatever may form an effective reservoir or source of underground water.

Confining Strata.—The best confining stratum is a bed of clay, marl, or shale ; but any compact unfissured rock, or even any contantly saturated semi-porous stratum, may act as an effective confining stratum provided it is *less* porous and offers a *greater* frictional resistance to the flow of water than the water-bearing stratum.

Water will always flow with the greatest freedom through the stratum that offers the least frictional resistance.

Standing water will always rise to its own level independently of friction, but running water cannot do so on account of the loss of *head* or pressure in overcoming the resistance offered to the flow by the interstices of the rock. As the size of the pores or interstices diminish, the frictional resistance increases with extraordinary rapidity, being inversely proportional to the diameter. For example, the frictional resistance to the flow of water in a half-inch tube is four times that of an inch tube of the same length. Herein we discover why a semi-porous stratum with small interstitial pores or openings may be an effective confining stratum for a water-bearing bed.
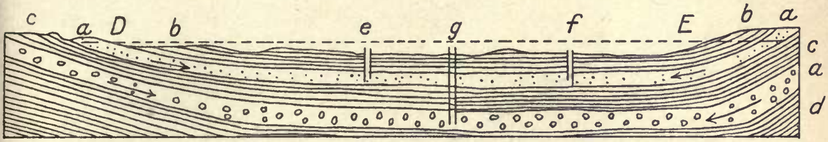
Fig. 249.—Section of artesian basin.

(*a–a*) Porous strata.
(*b*, *c*, and *d*) Confining beds above and below *a–a*.
(D E) Height of intake or fountain-head.
(*e*, *f*, and *g*) Flowing wells; *e* and *f* from upper water-bearing stratum, *g* from lower.

Arrangement of Strata.—The ideal arrangement of the strata to give the necessary pressure or head for an artesian well is the basin or trough, and next to that the sloping plain.

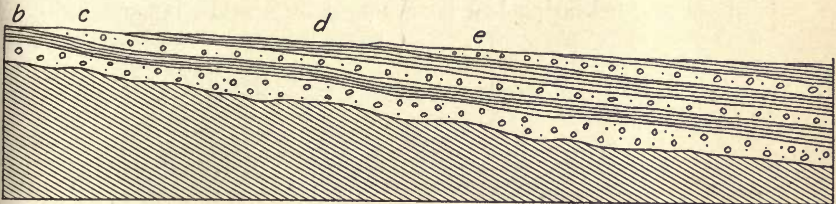

Fig. 250.—Section of artesian sloping plain.

(*a*) Porous bed resting on bed-rock.
(*b* and *d*) Confining beds of finer sand and clay.
(*c* and *e*) Porous beds.

One, two, or more water-bearing beds may occur in the same basin or sloping plain.

The sloping alluvial plain is common on the coasts of most countries, and nearly always contains water-bearing beds. The alluvium usually consists of alternations of sand, gravel, and clay, with frequently peaty layers. The material is mostly fluviatile, hence the beds vary greatly in thickness and extent. Going seaward the material usually becomes smaller in size; and a bed of gravel may pass into a bed of sand, and a bed of sand into clay or silt.

If the water-bearing beds crop out at the surface, they merely form ordinary surface springs; but when they extend beneath the sea, as so frequently happens with maritime plains, the fresh water rises against the pressure of the sea water, which seals up the open ends of the beds, preventing the escape of the fresh water wherever the *head* of the fresh water is less than that of the sea water. On account of its greater density, a column of sea water 100 feet high will support a column of fresh water nearly 103 feet high.

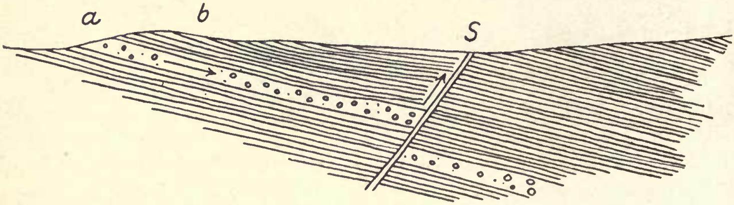

FIG. 251.—Showing fault-spring.
(*a*) Porous stratum. (*b*) Impervious bed. (*s*) Spring.

If the water-bearing bed is traversed by a fault, igneous dyke, or mineral lode, the downward course of the water may be stopped, and if the wall-rock is pervious, the water will rise upwards until it reaches the surface.

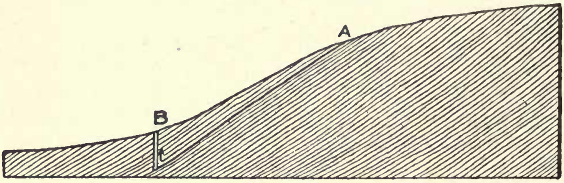

FIG. 252.—Showing flow along bedding planes.
A, Porous strata. B, Artesian well.

Artesian water may often be obtained in tilted strata, such as slates or schists, where the rain-water follows the bedding or foliation planes.

Source of Underground Water.—The main source of artesian water is the rain-water which percolates into the ground. The supplementary sources of supply are:—

(*a*) The residual water left in sedimentary rocks since the time of their deposition.
(*b*) Water released by dehydration of rocks and minerals.
(*c*) Plutonic or juvenile water derived from the interior of the earth.

Sediments laid down on the floor of the sea and in lakes entangle from 10 to 40 per cent. of their volume of water. Ordinary sands hold about one-third their volume of water. During consolidation and uplift, the greater portion of the water will escape, except where the beds are arranged in a trough or syncline. Most consolidated sedimentary rocks retain from 5 to 10 per cent. of water.

Minerals when first formed are in the hydrated condition, but through the influence of heat and pressure, they become dehydrated particularly during the process of crystallisation or metamorphism. Gelatinous and opaline silica becomes changed to quartz ; amorphous limestones to crystalline limestones, mainly composed of calcite ; peat and lignite become hard anhydrous coals.

Probably the bulk of the water expelled during dehydration passes upwards and is absorbed in the unaltered porous strata above, where it may remain under pressure until liberated by artesian wells.

During subsidence resulting from crustal movements, sandstones and other porous rocks charged with meteoric water, or with the water of deposition, may reach a zone where the water is expelled by heat and rock-pressure. The tendency of such expelled water will be to ascend into the higher unaltered beds, where it may accumulate, or it may rise to the surface and escape unobserved, or as natural springs.

The main source of the artesian water derived from alluvial drifts is obviously meteoric. The quantity of water derived from deep-seated sources is in this case probably so small as to be negligible.

The artesian water derived from bore-holes in the older formations in arid regions may be partly meteoric and partly uprising deep-seated water.

Nearly all lavas and igneous magmas contain a considerable quantity of water, but whether this water is brought up from the deep interior or merely derived from the rocks with which the uprising magma comes in contact, is unknown. It is quite certain that a cooling magma expels enormous volumes of steam, much of which must be condensed in the cooler zones of sedimentary rocks, where, in favourable circumstances, it will accumulate and supplement the supply derived from rainfall.

Factors in Artesian Flow.—The controlling factor in artesian flow is hydraulic pressure or *head*. Among the many modifying causes are :—

Constant Factors : (*a*) Size of pores or openings in the water-bearing stratum.
(*b*) Frictional resistance, which is dependent on the size of pores and distance of flow from fountain-head.
(*c*) Rock-temperature, which affects the viscosity and density of the water.
(*d*) Rock-pressure.
(*e*) Conditions of leakage.
Variable Factors : (*a*) Barometric pressure, diurnal and seasonal.
(*b*) Surface temperature affecting the density of water.

Local Artesian Waters.—The best water-bearing rock in England is the oolitic limestone in Lincolnshire, which contains many spouting wells.

The Chalk is water-bearing in places, but irregular and often nearly dry.

The Keuper marl yields good brewing water at Newark, Burton, and Leicester, but the amount is small and variable. The Keuper sandstone gives a good supply of soft water.

The Permian Sandstones and Magnesian Limestone in some places yield a copious supply of good water.

The Lower Greensand sometimes furnishes a considerable flow, and, as a rule, the more abundant the supply, the better the quality. With a small flow the water is often ferruginous.

The Lias clays are liable to produce saline waters, as also is the London Clay.

The Lower Eocene beds in the London Basin, below the London Clay, yield a fair supply which is often slightly alkaline.

An abundant supply of artesian water is obtained in the United States along the Atlantic fringe and Mexican Gulf Plain from the Cretaceous and Tertiary rocks, at depths varying from 50 feet along the inland border to 1000 feet on the coast-line.

In the Great Plains region of the Western Region the Dakota Sandstone is a valuable source of artesian water, which is extensively used for irrigation in the arid regions of South Dakota, Nebraska, and Kansas.

In Western Queensland enormous quantities of artesian water are obtained from the Mesozoic sandstones underlying the Cretaceous Rolling Downs Formation.

Medicinal Springs.—Many mineralised waters possess valuable therapeutic properties. Most medicinal springs occur in volcanic regions; among the best known being those of the Yellowstone National Park and Rotorua, New Zealand.

Medicinal waters according to their composition may be grouped as follows :—

(1) *Alkaline*, containing carbonate of soda and carbonic acid—Vichy, Saratoga; and Puriri, Rotorua, N.Z.
(2) *Bitter*, containing sulphate of magnesia and soda—Sedlitz; Rotorua.
(3) *Muriated*, with mainly common salt—Cheltenham, Wiesbaden, Hanmer, N.Z.
(4) *Calcareous*, with sulphate or carbonate of lime as the main constituent—Bath.
(5) *Sulphurous* or *Hepatic*, with alkaline sulphides and sulphuretted hydrogen, and frequently free sulphuric acid—Harrogate, Aix-la-Chapelle, and Rotorua.

Many mineral waters in Europe, America, and New Zealand have been shown to possess radio-active properties.

The temperature of mineral springs varies from 50° or 60° Fahr. to 212° Fahr. The temperature of the alkaline waters, as their deep-seated origin would suggest, is usually high, ranging from 180° to 212° Fahr.; while that of acid waters, which usually derive their acid constituents from contact with superficial oxidising masses of pyrites, is generally low, as a rule ranging from 90° to 110° Fahr.

But the temperature is dependent on local conditions; hence that of some alkaline waters, like Puriri, is low, while that of some acid waters is abnormally high.

Rock Temperatures in Mining.

During the driving of the St Gothard railway tunnel, the temperature of the rocks was found to increase at the rate of 1° Fahr. for every 60 feet from the surface, and for some considerable time this rate was regarded as normal for all parts of the earth's crust, and for all depths. These beliefs are now known to be erroneous. Observations taken in deep mines and bore-holes in various parts of the globe have shown :—

(*a*) That the temperature-gradient is not the same in all places.

The following temperature-gradients have been recorded :—

Comstock lode .	1°	Fahr.	for every	30	feet	in depth.
Thames lodes . .	1°	,,	,,	45	,,	,,
St Gothard tunnel .	1°	,,	,,	60	,,	,,
Bendigo mines .	1°	,,	,,	75	,,	,,

Tamarack Mine, Lake Superior . .	1°	Fahr.	for every	100	feet in	depth.
Rand Gold mines .	1°	,,	,,	200	,,	,,
Calumet and Hecla Mine, Lake Superior . .	1°	,,	,,	223	,,	,,

From the above it will be seen that some parts of the crust are abnormally hot, while others are abnormally cold.

In the Wheeling oil-well, Western Virginia, 4462 feet deep, both when wet and dry, the increase of temperature was 1° Fahr. for every 80 to 90 feet in the upper portion, and 1° Fahr. for every 60 feet in the lower.

Observation taken in bore-holes near Czuchow, in Rybnik, Silesia, 7280 feet deep; near Paruschovitz in the same coal-field, 6510 feet deep; at Schubin in Posen, 6988 feet deep; at Schladenbach, near Leipsic, 5630 feet deep, and other deep bore-holes, have confirmed the view—

(*b*) That the temperature-gradient increases with the depth.

CHAPTER XXXVI.

ELEMENTS OF FIELD GEOLOGY AND GEOLOGICAL SURVEYING.

The essential requirements of geological surveying is the ability to run natural sections accurately and methodically. And the running of natural sections is an art calling for the open mind, the shrewd, observant eye, sound judgment, a good knowledge of first principles, and a large measure of common sense.

The chief concern of the field geologist is to observe and plot the boundaries, strikes, and dips of all strata, or groups of strata, present in the area under review; to map the position of dykes and other igneous rocks, of faults, lodes, coal-seams, and mineral deposits. His report or thesis deals with the character, thickness, arrangement, age, distribution, and relationships of the stratified formations; with the character, composition, mode of occurrence, tectonic and other effects of intrusive rocks; and with the clays, stones, ores, and minerals of economic importance. Having mastered the geological structure, the geologist may, with some confidence, review the character and genesis of the topographical features.

The best way to learn the methods of exact observation is to attempt the geological survey of some area of simple structure. But before making this attempt it will be necessary to acquire some experience in field observation, and a good way to gain this is to go over some area that has been already mapped and described by an experienced field geologist. Follow the clearest lines of section, carefully note and record the succession and arrangement of the strata, and verify all your observations by comparing them with those recorded on the maps. In many cases you will find that the veteran geologist, aided by a wide experience of geological structures and a knowledge of the succession gained by his investigation of the same formations elsewhere, has been able to read a meaning into isolated facts and occurrences that to you are almost meaningless. Remember that all the facts relating to the geological structure of a district are not always fully disclosed in any one section. Some important point, relating to the geological succession, may be established in one section, and another point in some other section. Do not form conclusions based on obscure or complicated sections. Sections that leave room for two obvious lines of interpretation by two independent observers are frequently the cause of much useless contention, and ought to be avoided when possible. When all the sections in a district are obscure, the interpretation will sometimes be supplied by the clearer sections of a neighbouring or even distant area. When the stratigraphical succession is involved, the problem should be assiduously attacked from the palæontological standpoint.

Before you go to the field take care to get copies of the best geological and topographical maps obtainable of the area you have selected for your preliminary survey. Read all the reports dealing with the structure of the district, and make a summary of the geology for your guidance in the field. If you possess a fair knowledge of first principles, a good eye for country, and the persistency that overcomes all difficulties, you will soon be able to carry out useful, trustworthy work. Do not expect to unravel all the intricacies of the geology in a day or a week. You will usually find that as the mapping progresses, the geological structure will gradually unfold itself.

Field Equipment.—The equipment for field work should include a 3-inch prismatic compass with metallic card for observing strikes and dips, a 5-inch Abney level for measuring angles of dip, a 3-inch pocket spirit-level, a field-book with a stout cover, a short scale, a 4-inch brass protractor, a 3-inch aneroid barometer, a 66-feet tape, a geological hammer, geological pick, a set of light steel chisels for collecting fossils, and a stout leather bag.

An indispensable part of the equipment is a large scale topographical map on which the field observations are plotted as the work proceeds. A scale of twenty chains to the inch will be found suitable for ordinary surveys, and a scale of ten chains to the inch for more detailed work.

Make a tracing on paper of the portion of ground to be examined during one or two days, and fix it with paste round the edges in a stiff board portfolio. The observations are marked on the tracing as they are made in the field and afterwards transferred to the topographical map. Each tracing should show the cardinal points of the compass, to enable the strikes and dips to be plotted with the protractor, either in the field or on your return to your headquarters.

The collecting of fossils may be carried on at the same time as the field survey, but, as a rule, it is best to complete the field traverses and thereafter devote your undivided attention to the collecting of fossils. When the mapping and collecting are carried on at the same time there is always a danger that one or both may suffer. Besides, after the district is examined and mapped, you will possess a better knowledge of the fossiliferous beds and of the places where they are likely to prove the most productive. If the examination were of the nature of a rapid reconnaissance, it is the duty of the geologist, while running the traverses, to supplement his field observation with as ample collections of fossils, rocks, and mineral specimens as the time and circumstances will permit.

Rock and mineral specimens are usually collected during the progress of the field traverses, marked with small gummed labels, and then wrapped separately in pieces of paper on which the label number is also marked. The number and locality of the specimen are carefully recorded in the field-book.

A day or even a few days spent in a rapid reconnaissance of the district is usually time well spent. By this procedure you will obtain a broad view of the topographical features and general geological structure, which will enable you to arrange your campaign and mode of attack on a systematic basis. Moreover, before you begin the detailed survey you ought to have the lay of the country clearly impressed on your mind.

The field traverses follow all the main streams and their tributaries; also all the salient spurs, ridges, and prominent escarpments.

General Field Procedure.—The general field procedure comprises an examination of all cliffs, rock-outcrops, and escarpments, the position of which should be carefully marked on the field-map.

The points that should be specially recorded in the field-book are a description of the form and extent of the outcrop; character, thickness, strike, and dip of the different strata; height above sea-level or some other known datum; and the topographical features formed by the various rocks.

Make profile and longitudinal diagrams in your field-book of all prominent cliffs, outcrops, and escarpments. The profile is necessary in order to show the relationship and arrangement of the strata. These sketches need not be drawn to scale, but they should show the direction, height, and length of the portion of the section represented, together with references to the different beds, etc.

The position and extent of the fossiliferous beds should be noted, and a provisional list made of the more abundant fossils.

Take care to record the presence of all igneous masses, dykes, rills, or lava-flows; and indicate their position and boundaries on the map. Search for contacts between the igneous rock and the associated sedimentary rocks, and make a note of the effects due to thermal metamorphism, at the same time collecting rock specimens at short intervals to illustrate the progressive alteration of the clastic rocks. It is also important to select a series of specimens of the igneous rock from the selvedge inwards, in order to be able to ascertain by analysis and laboratory examination what effect, if any, the clastic rock has had on the intruding molten magma.

Faults are features of special interest frequently seen in the face of steep sea-cliffs or walls of deep ravines. Their vertical and horizontal displacement, strike, and dip should be recorded in the field-book, and their course marked on the map. Faults of large displacement show their existence by repetitions of the strata, or by bringing one rock-formation up against another. Such faults are disclosed by the mapping.

The thickness and character of the surface soils may be noted and recorded, but no attempt should be made to show the soils on the map, as this would obscure the distribution of the rock-formations. Special soil-maps are prepared for agricultural purposes.

A careful examination should be made of all accessible mine workings and mine plans, from which much valuable information relating to the geological arrangement of the strata may be frequently gleaned.

The outcrop of coal-seams, mineral deposits, and lodes should be indicated on the map, and a full description of the strike, dip, extent, and general character of the deposit recorded in the field-book. Representative samples of the coal or mineral should be collected for future examination.

Do not allow yourself to be hurried in making your observations. Undue haste may lead to errors in observation and the drawing of crude, ill-considered conclusions. Your interpretation of the geological structure may be altogether wrong and little harm come of it. The all-important point is to be sure of your facts. Always remember that every fact correctly recorded advances the geology of your district one step forward.

Learn to rely on the judgment of older and more experienced observers than yourself, and in your writings do not forget to acknowledge your indebtedness to the work of previous workers in the same field. To utilise the work of others without frank acknowledgment, or to recognise the conclusions of others only when you differ from them, tends to lower the value of your own work.

Do not be too ready to challenge the views of the veteran geologists who have preceded you, and do not try to exalt yourself by holding up their differences. As you gain more experience the more will you respect the opinion of the older geologists.

When you come to construct opinions and draw conclusions, bear in mind that the obvious is not always true. Early writers in New Zealand found broken bones of the gigantic Dinornis at some old native camping-places in Otago, and hastily concluded that the early Maori was a moa-hunter. The association of Maori and moa bones led at once to the conclusion that the two were contemporary. But closer inquiry failed to confirm this view. Moa bones were scattered plentifully over many parts of Otago even at the advent of the first white settlers fifty years ago, and are still not uncommon in places. At the advent of the Maori, moa bones must have been even more abundant, and who can doubt that a native so highly intelligent and so observant of all natural phenomena would fail to see and collect them. It is significant that the prolific tradition and song of the Maori, rich enough in elaborate detail of the hunting and snaring of the wood-pigeon, kaka, huia, weka, kiwi, tui, and other small birds, should be silent as to the gigantic moa. If the Maori had ever hunted and killed this stately bird, it is certain that his descendants would have preserved the fact in many picturesque traditions.

Accidents may lead to curious associations. The Yakubs of the frozen taiga of Northern Siberia trade in mammoth ivory. They have even dined off the frozen flesh of this extinct elephant. Perhaps early man did the same in Europe long after the retreat of the Pleistocene ice-sheet. The intimate association of the North Siberian and the mammoth does not prove that they are now or ever were coeval.

The Observation of Strike and Dip.—This is relatively simple where good rock outcrops are exposed at the surface, but certain precautions must be observed to ensure accuracy. The strike is the horizontal line along the bedding-plane of the rock; and the first precaution is to satisfy yourself that the plane before you is a true bedding-plane and not a joint-plane. In most cases the bedding-plane can be distinguished by some difference in colour, texture, or composition of the material.

The bedding-planes of shales, flaggy sandstones, flaggy limestones, and of all thin-bedded alternating argillites, sandstones, and limestones are easily distinguished. In most cases a clastic rock splits more or less readily in the direction parallel with the original plane of deposition.

The bedding-planes of massive beds of conglomerate are frequently indicated by intercalated layers of sand or clay; of chalk, by lines of flints or fossils; of marine clays, by lines of shells, by layers of harder material, or by lines of hard nodules; of sandstones, by lines of material of different texture or colour, or by layers of fossils.

Many massive deposits of limestone, claystone, sandstone, and conglomerate exhibit no recognisable bedding-planes. When such a deposit lies between two stratified beds that are parallel to one another, its bedding-plane is usually conformable to that of the enclosing beds.

But it is not safe to assume on the mere evidence of apparent parallelism of the associated strata that the unstratified rock is invariably conformable to the one on which it rests. The two rocks may, after all, belong to different formations, separated by a wide hiatus notwithstanding the apparent physical conformity at the outcrop.

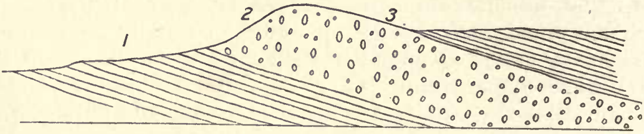

FIG. 253.—Unstratified rock lying between two stratified beds.
1 and 3, Stratified rock. 2, Unstratified rock.

Observing the Strike.—Expose as long a surface of the bedding-plane as possible, and on it, with the aid of the pocket spirit-level, draw a horizontal line with a sharp fragment of stone; or if there is a long exposure of rock, mark the horizontal line along the outcrop with small stones or stakes set at intervals. Observe the bearing or course of this line with a pocket-compass, or, better still, and more accurately, with the prismatic compass. Record the bearing, which is the strike required.

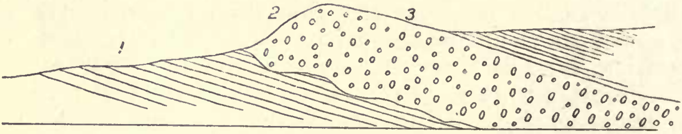

FIG. 254.—Showing unstratified rock unconformable to underlying rock.
1 and 3, Stratified rock. 2, Unstratified rock.

Highly inclined beds frequently follow a sinuous course along the strike, and care must be taken to obtain the general strike by taking the mean of a number of observations, or by setting out a long line along the outcrop.

The strike may be recorded as, say, N.E.–S.W., or as 45°–225°, which simply means that when you are looking northward along the outcrop the reading is 45°, and when looking southward 225°. All bearings originate from the north point as zero, and, since the two ends of the magnetic needle are always separated by 180°, it is easy to supply the reverse bearing when the reading has been made in one direction only, which is usually the case when using the prismatic compass. For example, if the compass reading be 30°, the reverse reading will be 210°, and the strike may be recorded as 30°–210°; if the bearing be 165°, the reverse bearing will be 345°, the strike being 165°–345°; or if the reading be 275°, the reverse reading will be 95°, hence the strike will be 95°–275°.

The rule to find the reverse bearing is as follows:—When the observed bearing is less than 180°, add 180° to obtain the reverse bearing, and when more than 180°, subtract 180°.

Instead of recording the strike (*i.e.* bearing) as 45°–225°, it may be recorded as 45°, or as 225°, following the practice of professional surveyors and engineers. To record the strike as N.E.–S.W., or 45°–225°, is a redundancy; for, obviously, if the strike or course runs N.E., it must also run S.W., and if 45°, also 225°.

Moreover, when the strike is plotted on the map with the protractor only one direction is used to obtain the course, that is, either 45° or 225°, previously corrected for the magnetic variation.

It will therefore fulfil all requirements and avoid confusion if you simply record the strike as 45°, 62°, 186°, or 347°, as the case may be.

In your amateur field excursions you may use a pocket-compass for observing the strike and dip, but in your more serious work it will be necessary to adopt the field procedure of the experienced geological surveyor.

Be careful to check all your observations and records by repetition. It is never safe to depend on a single observation. Observe the strike and record the reading in your field-book. Again, observe the bearing, note the reading, and compare it with the recorded bearing. By this procedure both the observation and the record are checked.

Take special care to satisfy yourself that the ledge of rock or outcrop where you have made your observation is *in situ* and not a fallen block. In deep gorges and steep sea-cliffs weak rocks, such as shales, thin bedded clays, and soft sandstones, fissile slates, mica-schists, and phyllite, are frequently distorted where the walls run parallel to or run obliquely across the strike. In such cases the most trustworthy observations for strike and dip are obtained from the water-worn ledges exposed in the bed of the streams, or on the rocky marine platforms at the foot of the sea-cliffs.

Observing the Dip.—The direction of the dip is always at right angles to the strike, and may incline to the right or left of the strike; that is, if the strike were N.–S. the dip might be towards the east or the west.

The angle of dip is measured with the swinging pointer or bob in the compass-box, or more accurately with the Abney level.

Make your observations for dip and strike at points where the rocks are clearly *in situ.* Avoid large tabular masses detached from the main outcrop. These may have become canted by the partial undermining of an underlying softer stratum by weathering or underground chemical corrosion.

False-bedding will seldom be misleading, except on small exposures.

Be specially careful concerning the direction and amount of dip in the walls of deep gorges and steep cliffs. In such situations the outcrops of the strata are frequently bent and warped by the weight of the superincumbent rocks; and by their own weight where they are unsupported. Outcrop curvature is common in all mountain regions where the rocks are weak. At places where the outcrop sag is considerable the direction of the dip may be reversed. It is always difficult to obtain trustworthy observations of strike and dip in gorges, ravines, and steep mountain slopes occupied by such weak rocks as phyllite, fissile slates, and shales, especially in recently glaciated regions where the weight of the ice has shattered, bent, and distorted the strata. Failure to recognise the difference between the true dip and the distortion caused by outcrop sag has led to the construction of some wonderful examples of hypothetical folding.

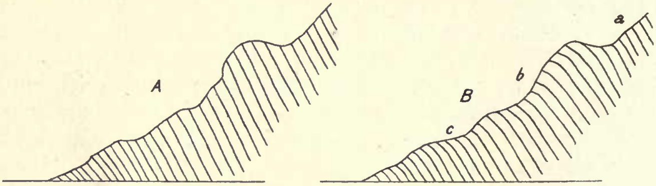

Fig. 255.—Showing effects of outcrop curvature.
A, Before curvature. B, After curvature.
(*a*) Beds not sagging because supported.
(*b*) Beds sagging on steep slope.

A safe rule is to reject all doubtful observations. Or if recorded in the field-book for future reference, they ought to be marked with a note of interrogation. On no account should they be used as a basis for the interpretation of tectonic structures.

A useful point to remember is that when beds have been tilted at high angles that approach the vertical, a small amount of push in one direction or the other, or an extra amount of pressure, will have caused them to incline to one side or the other. Observe the behaviour of highly inclined strata in the core of a steep anticline. Although you are dealing with a simple anticline, the strata exposed in the core as exposed by denudation along a river course or sea-cliff may be seen to vary from 75° to vertical, then incline in the opposite direction for a short distance, once more become vertical, and again incline a little in one direction or the other. Such rapid variations of inclination are not the result of sharp anticlinal folding, but merely an evidence of unequal pressure and packing of the strata in the zone of greatest stress. A series of true anticlinal folds in which the limbs approach the vertical position is easily distinguished by the tracing of the repetition of some distinctive stratum.

Measuring the Angle of Dip.—The angle of dip is most accurately measured with the Abney level. The longer the exposed bedding-plane the better. Where possible it is advisable to place a light pine lath 3 feet long along the direction of dip. When the lath is in its proper place the Abney level is laid on it, the arc moved by hand until the bubble is central, and the angle of inclination then read off the scale. By using the lath the minor inequalities of the bedding-plane are avoided.

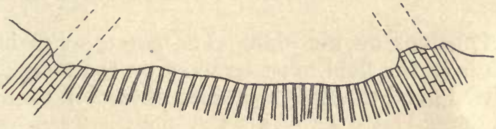

FIG. 256.—Showing variations of dip of highly-inclined strata in the centre of a steep anticline.

Observations made in deep mines and in profound mountain gorges, where distinctive beds can be frequently traced by the eye through a vertical height of many thousand feet, have shown that the strata are frequently subject to great variations in the angle and direction of the dip from the surface downwards. In many cases the dip will repeatedly change from one direction to another in a depth of a few thousand feet.

As a rule, strata that are inclined at high angles at the surface flatten with increasing depth.

Measuring Thickness of Strata.—This is a simple operation, the computation in the case of tilted strata being based on the angle of dip, the angle of the slope of the ground, and the measured distance on the slope.

The different cases that may arise, together with worked-out examples and diagrams, will be found in another work by the author,[1] and need not be repeated here.

When measuring the thickness of strata take care of repetitions arising from faulting or isoclinal folding. In the case of lacustrine, fluviatile, and estuarine beds, beware of estimating the thickness across the tipping-plane, which is a pseudo bedding-plane. This precaution also applies to all flysch and desert sandstones.

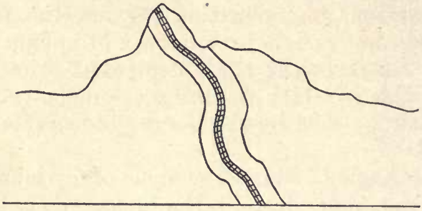

Fig. 257.—Showing changing dip in vertical height.

Locating Positions on the Map.—The points at which observations are made in the field must be fixed on the map. If you are provided with a good topographical map there will usually be little difficulty in doing this. As a rule the point is fixed by noting its position in relation to some known point. A known point is some spot which you can with certainty locate on the map. It may be a stream, junction, house, corner of some field, fence, or stone wall, angle or bend in the road, quarry reserve, prominent hill or peak, escarpment, trigonometrical station, bay, or headland, etc.

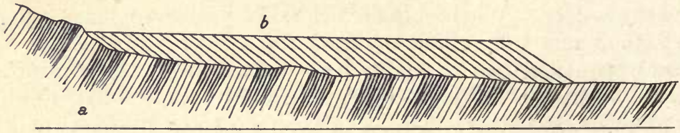

Fig. 258.—Showing pseudo bedding-plane.
(*a*) Bed-rock. (*b*) Deltaic sediments.

If you take care to start your traverse at some known point, the points of observation will be easily fixed on the map in orderly succession. If your map is deficient in details, it may be necessary for you to measure the distance from point to point with the measuring tape. Prominent outcrops on a distant range may be

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[1] James Park, *Text-Book of Mining Geology*, 3rd edit., chap. iv. p. 153. Charles Griffin & Co., Limited, London, 1911. 6s.

easily and accurately fixed by what is called intersections. The procedure is as follows:—Select some prominent outcrop that you can readily distinguish from different points of view. If there is no prominent object, erect a stake with a piece of white or red cotton material tacked to it. Observe the bearing of the object or flag from at least two points which you can with certainty fix on the map. Correct these bearings for magnetic variation so as to reduce them to the true meridian, and carefully plot them with the protractor on your map, using a hard pencil drawn to a fine point. The point of intersection of the two bearings gives the position of the mark or object.

With increasing experience you will acquire considerable skill in locating your field-points on the map.

The strike and dip are shown as in A of the next figure, the axis of anticlines as in B, and the centre of synclines as in C.

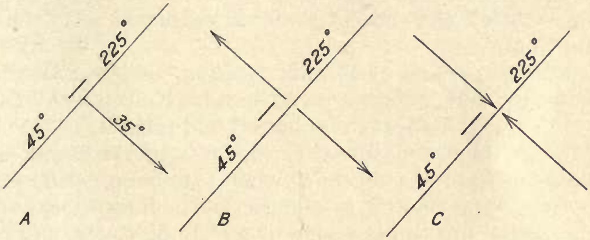

Fig. 259.—Conventional marks for strike and dip.

The bearing of the strike is marked on the line parallel with the strike, and the angle of dip on the line indicating the direction of the dip, as shown in fig. 259.

The Geological Map and Sections.—Your first business is to draw up a table of the geological formations present in the area you have examined. Each formation is usually distinguished on the map by a distinctive colour or conventional sign. But a formation may comprise two or more distinct beds or horizons of an outstanding character, each covering a considerable surface area. In such cases it may be expedient to show the subdivisions of one or more of the formations in different colours; or one colour may be used to distinguish the formation, its subdivisions being shown by various hatching or other conventional signs. The point to aim at is clearness. The attempt to show too much frequently leads to confusion.

The usual practice is first to plot the stream and ridge traverses, then the formation boundaries, and afterwards the subdivisions of the formations.

When the map is finished there only remain the sections to be plotted. Select the lines of section with the view of showing the geological structure, and the relationship of the different formations to one another. The sections are simply profiles of the upper crust, and they ought to be drawn as if you were looking northward.

In systematic surveys the sections are always drawn to natural scale; that is, the horizontal and vertical scales are the same. When the vertical scale is a half, a third, or a fourth of the horizontal, the inclination of the beds is exaggerated and the folds are distorted. Sections drawn on any other than natural scale cannot claim to be much more than diagrammatic.

Use the sea-level datum whenever possible, and let the vertical scale equal the horizontal in all cases except where the surface features are very low and flat.

Select the section-lines, and mark them on the map with a clear pencil line. Mark the ends of the first section A–A, of the second B–B, and so on.

Draw the datum line of the first section, scale off the distance A–A, and at the ends erect perpendiculars. Note that all the work is plotted in pencil before it is coloured and inked in.

Next draw the surface lines, the heights of the various points being obtained from the contour lines on the map or from aneroid or other data. Mark off the boundaries of the formations, as shown along the section line, on the edge of a strip of paper, and transfer the marks to the section. Draw lines on the section to indicate the boundaries and dips of the formations; apply selected colours for the different formations, ink in the boundaries; and, finally, put on the conventional marks if any are to be used. The fine maps and sections published by Geological Surveys of Great Britain and the United States will be a good guide as to what your map and sections ought to be like.

Preparation of Topographical Maps.—No geological work of any moment, either stratigraphical or petrographical, can be carried out without good topographical maps. Of some regions there are no maps, and sooner or later you will be called on to make your own topographical surveys.

A very useful and fairly accurate topographical survey may be made with the prismatic compass and a 5-chain steel tape, $\frac{1}{8}$-inch wide. A compass traverse is also made of all main and subsidiary streams and roads. The position of houses, fences, and all important natural features are fixed by offsets from the traverse lines when within a distance of two chains, and by intersection bearings when further off.

The stations are marked by stones or small stakes, and numbered in consecutive order; and the usual practice is to post up the day's work at night so as to note the gradual development of the survey and prevent the undue accumulation of field notes.

The angles of elevation, or depression, between the stations are measured with the Abney level; and since all maps are drawn on the horizontal projection, all slope measurements must be reduced to the equivalent horizontal distance for purpose of plotting.

Rule.—The cosine of the angle of elevation (or depression) multiplied by the slope measurement equals the horizontal distance.

The natural or logarithmic cosine may be used in the computation.

The bearings are plotted with a large brass protractor, not less than 6 inches in diameter, to a scale of 10 or 20 chains to the inch, according to the size of the district and the amount of geological detail to be put on it. Whenever it is possible contour lines should be run with the Abney level. The contour intervals will vary with the surface relief from 20 to 200 feet. In low undulating ground the interval may be 20, 30, or more feet, and in mountain regions 100 or 200 feet. The point to be observed in selecting the contour interval is to see that it is not so great as to miss prominent features. If wide intervals were used in low undulating ground many important spurs and hills might be passed over. Conversely, the selection of too close intervals in a mountainous region might involve the running of an unnecessary amount of lines.

If the geological work you are called upon to undertake is important, your topographical map should be made by theodolite survey with all the traverses oriented on the true meridian. You will find it easier to use a theodolite than a petrographical microscope, and after a little practice you will be able to carry on the work with ease and precision, while the greater accuracy of your work will be a perpetual source of pleasure.

The traverses follow the main streams and ridges, the prismatic compass being used for filling in minor details. The compass bearings are reduced to true bearings by applying the magnetic variation in the manner described in a preceding chapter.

On the excellent topographical maps provided in Europe and many States in America, the magnetic variation is only given at the major trigonometrical stations. As a matter of fact the variation is liable to differ widely in different parts of the same district owing to the proximity of igneous dykes and bosses, some of which may not be exposed at the surface. A serious local deflection of the needle may be also caused by iron bridges, tram and railway lines, iron houses, iron fences, and other artificial structures in which iron is present in considerable quantity. Hence, you will find it advantageous to determine the variation at many different points during the progress of your theodolite survey. This is quite a simple operation, and may be carried out as follows :—

When the theodolite is set over a station observe the true bearing of some prominent distant object, such as a tree top, church spire, or sharp peak. Record the bearing and the number of the station.

Now unclamp the vernier plate and set it at zero. Then loosen the long box-needle, and swing the instrument round until the needle settles in the N.–S. line. Clamp the bottom plate, and with the bottom tangent-screw orient the instrument exactly in the magnetic meridian. This is effected by bringing the engraved line at the end of the compass-box exactly opposite the north end of the needle.

Now unclamp the vernier plate, direct the telescope to the object previously viewed, and read the bearing. Repeat the operation, and take the mean of the two readings. The difference between this mean magnitude bearing and the true bearing is the magnetic variation at the station of observation, disregarding the small correction for convergence of meridian.

The true meridian is determined at the initial station of the theodolite survey, in the Northern Hemisphere by observations to Polaris, and in the Southern Hemisphere to α *Crucis*, α *Centauri*, or other conspicuous circumpolar star. You will have no difficulty in determining the meridian within half a minute of arc. Detailed instructions as to the methods and procedure to be pursued, together with worked-out examples and diagrams, will be found in a little work by the author,[1] in which also the methods of contouring with the Abney level are fully described.

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[1] James Park, *Text-Book of Theodolite Surveying*, 2nd edit., Charles Griffin & Co., Limited, London, 1911.

APPENDIX A.

To Convert Magnetic Bearings to True Bearings.

All geological and topographical maps are projected on the so-called true meridian; hence, when the strike of strata is determined with a magnetic compass, it becomes necessary to convert the observed magnetic bearing into a true bearing before it can be plotted on the map.

Conversely, if the strike of a seam or stratum is taken off the map with the view of setting off the course on the ground with a compass, the true bearing must first be converted into a magnetic bearing.

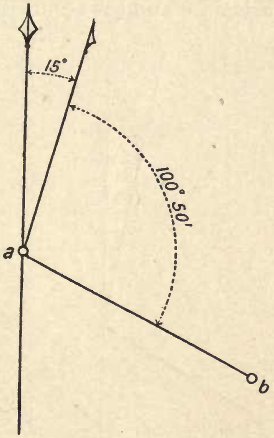

Fig. 260.—Conversion of magnetic bearings to true.

Only in a few places does the true meridian coincide with the magnetic meridian. In most regions the magnetic meridian lies to the east or west of the true meridian. The difference between the two meridians is called the *magnetic variation*, and its amount is usually marked on all topographical and trigonometrical district maps.

In Britain the magnetic meridian is west of the true meridian, and in New Zealand east.

The strike is best determined with a pocket or prismatic compass graduated into. 360° where 360° is north or zero. Obviously, east will be 90°, south = 180°, and west = 270°.

The advantage of a compass graduated in this way is that all the bearings (*i.e.* courses or strikes) are measured from the north point.

To Convert a Magnetic Bearing to a True Bearing.—Only two cases are likely to occur—namely, the variation will be east or west.

When the Variation is East.—Rule—To the observed magnetic bearing *add* the variation, and the result will be a true bearing.

In fig. 260 the variation is 15° east of the true meridian, and the compass bearing of line *a b* along the course of a stratum, 100° 50′; find the true meridian. Obviously—

$$100° \ 50' + 15° = 115° \ 50' = \text{true bearing};$$

that is, the corrected bearing in terms of the true meridian is 115° 50′.

When the Variation is West.—Rule—From the observed magnetic bearing *subtract* the variation, and the result will be the true bearing.

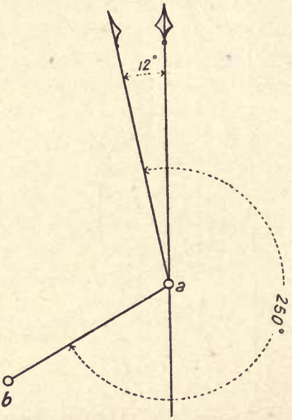

FIG. 261.—Conversion of magnetic bearings to true.

In fig. 261 the variation is 12° west of the true meridian, and the compass course of a lode is 250°; find the bearing or strike in terms of the true meridian. Here—

$$250° - 12° = 238° = \text{true bearing}.$$

To Convert a True Bearing to a Magnetic Bearing.—This is the converse of the above. When the variation is easterly, *subtract* the variation from the true bearing; and when westerly, *add* it to obtain the corresponding magnetic bearing.

APPENDIX B.

Determination of Strike and Dip from Contoured Map.

THE exactitude to be obtained by this method depends on the accuracy of the survey and mapping. The results are trustworthy only when the contours have been run with the spirit-level; the outcrops and contours accurately fixed by theodolite traverse; and the positions plotted by rectangular co-ordinates on a large scale.

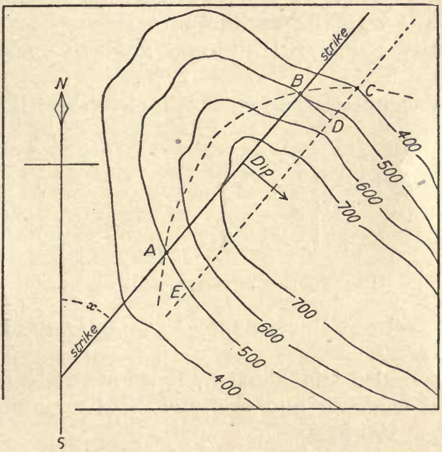

FIG. 262.—Showing graphic determination of strike from contoured map. A, B, C, Outcrop of bed.

To Determine the Strike.—Two outcrops on the same level must be known.

Let A and B be two outcrops of a bed or vein at the same level. Join points A and B with a straight line.

Then the line A B is the direction of the strike, and angle x the bearing of the strike in terms of the meridian N–S, which may be the true meridian or the magnetic meridian, according to the orientation of the map.

At all other levels the strike will be parallel to A B. Thus at point C, which is 100 feet below B, the strike is C E.

To Determine the Dip.—The dip, or more correctly the direction of the dip, is always at right angles to the strike. If we assume that the bearing of the strike is 40° (that is, angle $x = 40°$), then the dip being south-easterly, the direction of the dip is $40° + 90° = 130°$.

If the dip were in the opposite direction, the strike being the same, then its bearing or direction would be—

$$360° + 40° = 400°$$
$$\text{and } 400° - 90° = 310°.$$

To Determine the Angle of Dip.—Three points or outcrops must be known, namely, two at the same level and one at a lower or higher level.

(1) Let A, B, and C, fig. 262, be the known outcrops, A and B being at the same level, and C at a lower level, 100 feet below B.
(2) Determine the strike as in the first problem.
(3) Through C draw C E parallel to A B.
(4) At B draw a line B D at right angles to A B, terminating at line C E.
(5) Scale as accurately as you can the length of B D.

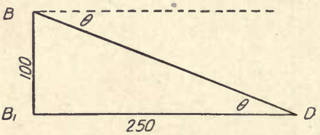

FIG. 263.—Showing profile along B D.

Let B_1 be a point at the same level as C or D, immediately below B, and let $B_1D = 250$ feet.

In the right-angled triangle B B_1 D we have given the two sides about the right angle to find the angle of dip, namely, $B_1D = 250$ feet, and B $B_1 = 100$ feet.

Let θ = the angle of dip.

Then—

$$\text{Cot } \theta = \frac{B_1D}{B_1B}, \text{ or tan } \theta = \frac{B_1B}{B_1D}.$$

By natural tangents—

$$\text{Tan } \theta = \frac{100}{250} = \cdot4000000 = 21° \, 48' = \text{angle of dip.}$$

By logarithms—

$$\begin{array}{ll} \text{Log } 100 & = 2\cdot0000000 \\ \text{Log } 250 & = 2\cdot3979400 \\ \hline \text{Log tan } 21° \, 48' & = \underline{9\cdot6020600} \end{array}$$

BIBLIOGRAPHY.

The following list contains the titles of most of the works to which reference has been made in the preparation of this volume. Many of these deal with the whole or a portion of the subject in a comprehensive manner. Reference has also been made to special points in the Reports and Memoirs of the official Geological Surveys of Great Britain, United States of America, India, and the Oversea Dominions; and to papers scattered throughout the *Quarterly Journal of the Geological Society*, the *Philosophical Transactions of the Royal Society*, *Comptes Rendus*, *Annales des Mines*, and various American, English, and Continental scientific and technical serials. These papers are so numerous that the exigencies of space make it impossible to attempt their bibliographical statement here.

History of Geology.

Bonney, Prof. T. G., *Charles Lyell and Modern Geology.* London, 1901.
Geikie, Sir A., *Life of Sir R. I. Murchison*, 2 vols. London, 1875.
—— *The Founders of Geology*, 2nd ed. London, 1905.
Merrill, G. P., *History of American Geology.* Washington, 1906.
Woodward, H. B., *History of Geology.* London, 1911.
—— *History of the Geological Society of London.* London, 1907.
Zittel, Karl von, *History of Geology and Palæontology* (English translation by Maria M. Ogilvie-Gordon). London, 1901.

General and Physical.

Arrhenius, S., *Worlds in the Making.* London, 1908.
Bischof, Gustav, *Elements of Chemical and Physical Geology* (English translation by B. H. Paul and J. Drummond), 2 vols. London, 1854–55.
Bonney, Prof. T. G., *The Story of our Planet.* London, 1902.
—— *The Building of the Alps.* Cambridge, 1912.
—— *The Work of Rain and Rivers.* Cambridge, 1912.
Chamberlin, T. C., and **Salisbury, R. B.**, *Geology—Processes and their Results*, 3 vols., 2nd ed. London and New York, 1906.
Dana, J. D., *Manual of Geology*, 4th ed. New York, 1895.
Davis, W. M., and **Smyder, W. H.**, *Physical Geography.* New York, 1898.
Dwerryhouse, A. R., *The Earth and its Story.* London, 1910.
—— *Geological Maps and their Use.* London, 1912.
Etheridge, R., *Phillips' Manual of Geology*—vol. ii.: "Stratigraphical Geology and Palæontology." London, 1885.
Fisher, Rev. O., *Physics of the Earth's Crust*, 2nd ed. London, 1889.
Geikie, Sir A., *Text-book of Geology*, 2 vols., 4th ed. London, 1903.
Geikie, Prof. James, *Structural and Field Geology*, 2nd ed. London, 1908.
Green, Prof. A. H., *Physical Geology.* London, 1898.
Gregory, Prof. J. W., *Geography—Structural, Physical, and Comparative.* London, 1908.
—— *Australasia*, 2nd ed. London, 1907.
—— *The Building of the Earth.* London, 1912.

Jack, R. L., and **Etheridge, R., jun.,** *Geology and Palæontology of Queensland and New Guinea.* London, 1892.
Johnston, P. M., *The Geology of Tasmania.* Hobart, 1888.
Joly, Prof. J., *Radio-activity and Geology.* London, 1909.
Judd, Prof. J. W., *The Student's Lyell,* 2nd ed. London, 1911.
Jukes-Browne, A. J., *Physical Geology.* London, 1892.
Kayser, E., *Text-book of Comparative Geology* (English translation by Philip Lake). London, 1893.
Lake, P., and **Rastall, R. H.,** *A Text-book of Geology.* London, 1910.
Lyell, Sir C., *Principles of Geology,* 11th ed. London, 1872.
Marr, Prof. J. E., *The Principles of Stratigraphical Geology.* Cambridge, 1898.
Murray, John, and **Hjort, J.,** *The Depths of the Ocean.* London, 1912.
Park, Prof. James, *The Geology of New Zealand.* London, 1910.
Prestwich, Sir J., *Geology*—vol. i.: "Chemical and Physical"; vol. ii.: "Stratigraphical and Physical." London, 1886–88.
Reclus, E., *The Earth* (translation by H. B. B. Woodward). London, 1871.
Roberts, R. D., *An Introduction to Modern Geology.* London, 1893.
Rogers, A. W., *The Geology of Cape Colony,* 2nd ed. London, 1908.
Russell, I. C., *River Development.* London, 1907.
Schwarz, Prof. E. H. L., *Casual Geology.* London, 1910.
Seeley, Prof. H. G., *Phillips' Manual of Geology*—vol. i.: "Physical Geology and Palæontology." London, 1885.
Sollas, Prof. W. J., *The Age of the Earth, and other Geological Studies.* London, 1905.
Suess, Prof. E., *The Face of the Earth,* 4 vols. (translated by Bertha B. C. Sollas). London, 1904–09.
Thiene, Hermann, *Temperatur und Zustand des Erdinnern.* Jena, 1907.
Vredenburg, E. W., *A Summary of the Geology of India,* 2nd ed. Calcutta, 1910.
Watts, Prof. W. W., *Geology for Beginners,* 2nd ed. London, 1909.

Petrology and Vulcanism.

Anderson, Tempest, *Volcanic Studies.* London, 1903.
Bonney, Prof. T. G., *Volcanoes,* 2nd ed. London, 1902.
Cotta, B. von, *Rocks Classified and Described* (English translation by P. H. Lawrence).
Daubeny, Charles, *A Description of Volcanos.* London, 1826.
Geikie, Sir A., *Ancient Volcanoes of Great Britain,* 2 vols. London, 1897.
Günther, R. T., *Earth Movements in the Bay of Naples.* Oxford, 1903.
Harker, Alfred, *The Natural History of Igneous Rocks.* London, 1909.
—— *Petrology for Students,* 2nd ed. London, 1897.
Hatch, F. H., *Text-book of Petrology,* 5th ed. London, 1909.
Hobbs, Prof. W. H., *Earthquakes.* London, 1907.
Iddings, Joseph P., *Igneous Rocks,* 2 vols. New York, 1909.
Judd, Prof. J. W., *Volcanoes.* London, 1881.
Knott, C. G., *The Physics of Earthquake Phenomena.* London, 1908.
Park, Prof. James, "Tarawera Eruption and After," *The Geographical Journal,* vol. xxxvii., No. 1, Jan. 1911, pp. 42–49; and *Geology of New Zealand.* London, 1910.
Pirsson, Louis V., *Rocks and Rock Minerals.* New York, 1909.
Rosenbusch, Prof. H., *Microscopical Physiography of Rock-forming Minerals* (English translation by Joseph P. Iddings). New York, 1900.
Scrope, G. Poulett, *Volcanoes.* London, 1862.
—— *The Geology and Volcanoes of Central France,* 2nd ed. London, 1858.
Symons, G. J., Editor, *The Eruption of Krakatoa and Subsequent Phenomena.* London, 1888.

Palæontology.

Cole, Prof. Grenville A. J., *Aids in Practical Geology*, 5th ed. London, 1910.

Etheridge, Robert, "Stratigraphical Geology and Palæontology," vol. ii. *Phillips' Manual of Geology*. London, 1885.

Hutchinson, Rev. H. N., *Extinct Monsters and Creatures of Other Days*. London, 1910.

Lankester, Prof. E. Ray, *Extinct Animals*. London, 1905.

M'Coy, Sir F., *Prodromus of the Palæontology of Victoria*. Melbourne, 1877.

Nicholson, H. A., and **Lydekker, R.,** *Manual of Palæontology*, 2 vols., 3rd ed. Edinburgh, 1889.

Owen, Richard, *Palæontology*, 2nd ed. Edinburgh, 1861.

Pictet, F. J., *Traite de Paléontologie*, vols. i.–iv., with atlas, 2nd ed. Paris, 1889.

Scott, D. H., *Studies in Fossil Botany*. London, 1900.

Seward, A. C., *Fossil Plants*, 2 vols. Cambridge, 1898.

Woods, H., *Palæontology: Invertebrate*, 3rd ed. London, 1902.

Woodward, A. Smith, *Outlines of Vertebrate Palæontology*. Cambridge, 1898.

Woodward, S. P., *A Manual of Mollusca*, 4th ed. London, 1890.

Zittel, Karl von, *Text-book of Palæontology* (English translation by C. R. Easman). London, 1902.

Scenery and Topography.

Avebury, Right Hon. Lord, *The Scenery of England*. London, 1904.

—— *The Scenery of Switzerland*. London, 1906.

Bonney, Prof. T. G., *Ice Work—Past and Present*, 2nd ed. Cambridge, 1903.

✓ **Geikie, Sir A.,** *Landscape in History*. London, 1905.

✓ —— *Scenery of Scotland*. London, 1865.

—— *Earth Sculpture*. London, 1902.

Gregory, Prof. J. W., *Geography—Structural, Physical, and Comparative*. London, 1908.

Macnair, P., *The Geology and Scenery of the Grampians*, 2 vols. Glasgow, 1908.

Marr, J. E., *The Scientific Study of Scenery*, 2nd ed. London, 1903.

Salisbury, R. D., *Physiography*. New York, 1908.

Glaciation and Glaciers.

Ball, Sir Robert, *Cause of the Ice Age*, 2nd ed. London, 1892.

Croll, James, *Climate and Time*. Edinburgh, 1875.

Forbes, Prof. J. D., *Travels through the Alps of Savoy, etc.*, 2nd ed. Edinburgh, 1845.

✓ **Geikie, Prof. James,** *The Great Ice Age*, 2nd ed. London, 1877.

Hobbs, Prof. W. H., *Characteristics of Existing Glaciers*. London, 1911.

Sollas, Prof. W. J., *Age of the Earth and other Geological Studies*. London, 1905.

Economic Geology.

Beck, Prof. Richard, *The Nature of Ore Deposits* (English translation by W. H. Weed), 2 vols. New York, 1905.

Beyschlag, Krusch, and **Vogt,** *Die Lagerstätten der Nutzbaren Mineralien und Gesteine*, 3 vols. Stuttgart, 1909.

Gibson, Walcott, *Geology of Coal and Coal Mining*. London, 1908.

Kemp, J. F., *The Ore Deposits of the United States and Canada*, 3rd ed. New York, 1900.

Maclaren, J. Malcolm, *Gold: Its Geological Occurrence and Geographical Distribution.* London, 1908.

Park, Prof. James, *Text-book of Mining Geology,* 3rd ed. London, 1911.

Phillips, J. A., and **Louis, H.,** *A Treatise on Ore Deposits,* 2nd ed. London, 1896.

Posepny, Van Hise, Emmons, Weed, Le Conte, Lindgrew, *Genesis of Ore Deposits.* New York, 1900.

Rickard, Weed, and others, *Ore Deposits: A Discussion.* New York, 1903.

Ries, Heinrich, *Economic Geology of the United States.* New York and London, 1905.

Suess, Prof. Eduard, Lecture, *The Geographical Journal,* vol. xx. p. 520, 1902.

—— *The Face of the Earth* (English translation by B. B. C. Sollas), vol. i. p. 207.

Thomas, H. H., and **Macalister, D. A.,** *The Geology of Ore Deposits.* London, 1909.

Watson, John, *British and Foreign Building Stones.* Cambridge, 1911.

Williams, G. F., *The Diamond Mines of South Africa,* 2 vols. New York, 1906.

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