
SMITHSONIAN INSTITUTION
THE LIBRARY
FOR THE INCREASE AND DIFFUSION OF KNOWLEDGE AMONG MEN
SMITHSONIAN INSTITUTION WASHINGTON 1846

STRUCTURAL AND FIELD GEOLOGY

STRUCTURAL AND FIELD GEOLOGY

FOR STUDENTS OF PURE AND APPLIED SCIENCE

BY

JAMES GEIKIE, LL.D., D.C.L., F.R.S., Etc.

MURCHISON PROFESSOR OF GEOLOGY AND MINERALOGY IN THE UNIVERSITY OF EDINBURGH;
FORMERLY OF H.M. GEOLOGICAL SURVEY

AUTHOR OF
"THE GREAT ICE AGE," "PREHISTORIC EUROPE," "EARTH SCULPTURE," ETC.

SECOND EDITION, REVISED

NEW YORK
D. VAN NOSTRAND COMPANY
23 MURRAY AND 27 WARREN STREETS
1908

PREFACE TO THE FIRST EDITION

THIS Handbook addresses itself, in the first place, to beginners in Field Geology, but I hope it may be found useful also to students who are preparing for professions in which some knowledge of Structural Geology is of practical importance. The amount of geological training demanded varies, doubtless, with the nature of the profession. Mining engineers, for example, must acquire a knowledge of many details which civil engineers, architects, agriculturists, and public health officers can afford to neglect. Nevertheless, if Structural Geology is to be of service to a professional man it must be studied in a systematic manner. Without an intelligent appreciation of the subject as a whole, it is very hard or well-nigh impossible to gain an adequate working knowledge of any particular part. In the following pages, therefore, the subject is set forth mainly from the point of view of pure science. The student of applied science, however, should have little difficulty in distinguishing between matter of general interest, and that which is of special importance to him, as bearing directly on his own professional pursuits. To help in this discrimination two sizes of type have been employed—the smaller type being commonly reserved for details or discussions of import mainly or exclusively to students of pure science. With regard to the matter in larger type, the intelligent student will use his own discretion. To others than mining men, for example, the chapters dealing with ore-formations will not call for much studious consideration. Again, neither civil engineers, public health officers, nor agriculturists may ever be called upon to make a geological survey of any district. Intending professional men will be ill-advised, however, if they do not take the trouble to understand the methods of observation employed in Field Geology, for such knowledge will often be of considerable service in their future careers. To mining and civil engineers, especially, an acquaintance with the methods of geological surveying and map-construction cannot fail to be invaluable, while agriculturists and public health officers ought assuredly to know enough of the subject to understand and interpret a geological map. I may be allowed to add that at the University of Edinburgh we have found no difficulty in teaching Structural and Field Geology to mixed classes of students of pure and applied science. The present Manual may be said to cover the ground gone over in our Summer Course of Geology—a course instituted some twenty years ago to meet the requirements of students desirous of obtaining a fuller knowledge of Practical Geology—more especially field-work—than could be presented in the general systematic course given in winter.

The Plates which illustrate this volume have been derived from various sources. A number are reproduced from unpublished photographs taken by Mr R. Lunn for H.M. Geological Survey. Permission to use these was obtained from the Board of Education through the kind offices of Dr Teall, Director of the Geological Survey, and Dr Horne, Assistant Director. No one can be more sensible than myself that these illustrations give an interest to this work which it would not otherwise possess. To my former colleague and lifelong friend, Dr Peach, I am indebted for the coloured section which accompanies one of these plates. Plates X. and XXIV. are reproduced, by the courteous permission of the Controller of H.M. Stationery Office, from published memoirs of the Geological Survey. My friend and former assistant, Dr Flett, now of H.M. Geological Survey, was good enough to supply me with the photograph reproduced on Plate XXXI., as well as with others which only the limited scope of my book has prevented me using. I am also under many obligations to him for reading some of my proof-sheets, and making various helpful suggestions. To another friend and former pupil, Dr Laurie, I am similarly indebted for the photographs reproduced on Plates XXV. and LIV., which were taken on one of the excursions of my Summer Class. Mr Francis J. Lewis, of the University of Liverpool, whose investigations into the structure and history of the peat-bogs of Britain promise to be of the greatest interest and importance to botanists and geologists, kindly put at my disposal several characteristic photographs of peat-bogs, from which I selected the illustration that appears in Plate LIV. Unless when otherwise stated, all the other Plates are reproductions from photographs of specimens in my own Class-Museum, taken under the superintendence of Dr J. D. Falconer, formerly my assistant and now Director of the Mineral Survey of Northern Nigeria. I may add that many of the illustrations in the text were drawn for me by my son, Mr W. Cranston Geikie.

EDINBURGH, *April* 15, 1905.

PREFACE TO THE SECOND EDITION

THIS edition differs but little from its predecessor. The author has taken the opportunity it has afforded him, however, to supply some omissions, and to make a number of emendations and corrections, which he hopes may render the work more acceptable to those for whom it has been prepared.

EDINBURGH, *February* 24, 1908.

CONTENTS

CHAPTER I

ROCK-FORMING MINERALS

CHAPTER II

ROCK-FORMING MINERALS—*continued*

CHAPTER III

ROCKS

CHAPTER IV

ROCKS—*continued*

CHAPTER V

ROCKS—*continued*

CHAPTER VI

FOSSILS

CHAPTER VII

STRATIFICATION AND THE FORMATION OF ROCK-BEDS

CHAPTER VIII

CONCRETIONARY AND SECRETIONARY STRUCTURES

CHAPTER IX

INCLINATION AND CURVATURE OF STRATA

CHAPTER X

JOINTS

CHAPTER XI

FAULTS OR DISLOCATIONS

CHAPTER XII

STRUCTURES RESULTING FROM DENUDATION

CHAPTER XIII

ERUPTIVE ROCKS: MODE OF THEIR OCCURRENCE

CHAPTER XIV

ERUPTIVE ROCKS: MODE OF THEIR OCCURRENCE—*continued*

CHAPTER XV

ALTERATION AND METAMORPHISM

CHAPTER XVI

ORE-FORMATIONS

CHAPTER XVII

ORE-FORMATIONS—*continued*

CHAPTER XVIII

GEOLOGICAL SURVEYING

CHAPTER XIX

GEOLOGICAL SURVEYING—*continued*

CHAPTER XX

GEOLOGICAL SURVEYING—*continued*

CHAPTER XXI

GEOLOGICAL MAPS AND SECTIONS

CHAPTER XXII

ECONOMIC ASPECTS OF GEOLOGICAL STRUCTURE

CHAPTER XXIII

ECONOMIC ASPECTS OF GEOLOGICAL STRUCTURE—*continued*

CHAPTER XXIV

SOILS AND SUBSOILS

CHAPTER XXV

GEOLOGICAL STRUCTURE AND SURFACE FEATURES

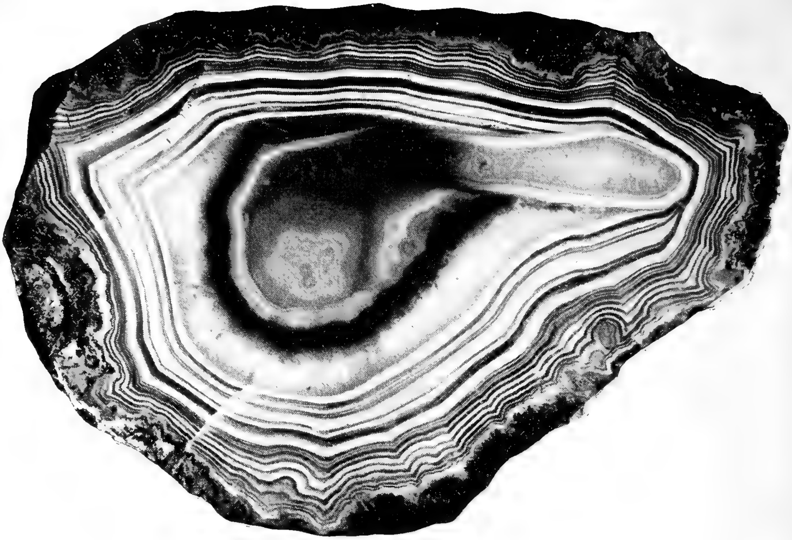
APPENDICES

LIST OF ILLUSTRATIONS

FULL-PAGE PLATES

ILLUSTRATIONS IN TEXT

PLATE I.



1.

2.

3.

1. Section of Agate from an amygdaloidal cavity Nearly natural size.
2. Rock-crystal, enclosing needle-like Rutile
3. Garnets in Mica-schist.

[*To face page* 1.

STRUCTURAL AND FIELD GEOLOGY

CHAPTER I

ROCK-FORMING MINERALS

Oxides—Quartz and its varieties; Opal; Specular Iron; Ilmenite; Magnetite; Limonite; Rutile; Zircon; Spinelloids; Corundum; Pyrolusite, Psilomelane, and Wad. Silicates—Felspar Group; Felspathoid Group.

BEFORE the phenomena presented by the framework of the earth's crust can be fully appreciated, one ought to have some knowledge of rocks and their various constituents. This is all-important for the student who is specialising in geology. For others who wish merely to obtain such aid in their several occupations as this science can supply, a more moderate acquaintance with minerals and rocks than the geologist requires may suffice, and it is for this class of students more especially that the following descriptions have been written. In these introductory chapters, therefore, special attention is paid to macroscopic or megascopic characters—those, namely, which may be observed in hand-specimens, with or without the help of a pocket-lens. As it is hoped, however, that some readers may be sufficiently interested to wish to know more, a few notes in smaller type have been added, giving further details and describing characters which can only be studied in thin slices under the microscope. It is quite a mistake to suppose that any great knowledge of mineralogy is required to enable one to determine the essential ingredients of a fine-grained rock in this way. With ordinary application one may in a short time acquire sufficient skill to diagnose microscopically all the more commonly-occurring rocks—those, namely, which are likely to come under the notice of architects, civil engineers, agriculturists, and others.

The rock-forming minerals are not a numerous class, and only a few are of pre-eminent importance. For example, the essential mineral constituents of the most abundant and widely distributed igneous rocks may be counted on the fingers. The components of common schistose rocks, and of the great class of derivative rocks, are even fewer in number. When the student is able to determine some twenty minerals under the microscope, he should have little difficulty in diagnosing most of the fine-grained rocks that he is likely to meet with. Slight though this knowledge may be, it will yet enable him to appreciate what petrographers have to say as to the genesis of crystalline igneous and schistose rocks, and will undoubtedly aid him in his own field-observations.

For convenience of description, the common rock-forming minerals have been grouped under the following heads: Oxides, Silicates, Haloids, Sulphides, Carbonates, Sulphates, Phosphates, and Elements. As the minerals included under these several heads are of very unequal importance, the descriptions of the less significant species are given in small type.

Rock-Forming Minerals

I. OXIDES

By far the most important rock-forming oxide is silica, next to which come various oxides of iron. The other oxides here described are of less frequent occurrence—some two or three being hardly entitled to rank as true rock-formers.

Quartz is chemically pure silica (SiO_2). It is harder than any other common rock-former, being 7 in the scale of hardness.* The minerals which are much harder than quartz play a very subordinate part in rocks, the only species that need be mentioned here being spinel and corundum. Quartz has a specific gravity of 2·65, and when it assumes a crystalline form, appears most frequently as hexagonal prisms terminated by corresponding pyramids (see Fig. 1). Most minerals can

---

* See Appendix B.

be split or cleaved more readily in some directions than in others. In certain cases cleavage takes place in one direction only; in other cases there are two and sometimes three directions in which a mineral may be more or less readily divided. Separation along such cleavage-planes is sometimes effected with facility, as in mica, gypsum, calcite, and fluorite—the cleavage-planes having smooth and lustrous surfaces. In other cases, cleavage may be more or less imperfect or even unrecognisable. When force is applied to minerals of this kind, therefore, they do not separate along planes, but break with an uneven or irregular fracture. Quartz is one example, breaking, as it does, with a shell-like (conchoidal) fracture. In its purest form the mineral is water-clear, and has a vitreous lustre. It is infusible before the blowpipe, and insoluble either in hydrochloric, sulphuric, or nitric acid.

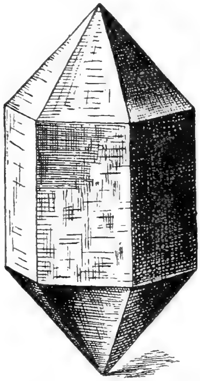


FIG. 1.—CRYSTAL OF QUARTZ.

A combination of hexagonal prism and hexagonal pyramid.

Quartz occurs in several ways :—1. Frequently it is a product of igneous fusion, being met with as an original constituent of many kinds of eruptive rock, such as granite, quartz-porphyry, rhyolite, etc. 2. It is a not less important ingredient of many schistose rocks, such as gneiss, mica-schist, etc., and is thus the result of metamorphic action—the nature of which will be considered in a subsequent chapter. 3. Quartz occurs also as a deposition from aqueous solution, and as such has a very wide distribution. Silica deposited in this way is derived chiefly from the chemical decomposition of rock-forming silicates. Such solutions, percolating through the rocks of the earth's crust, have brought about manifold changes. Frequently, for example, we find quartz replacing the original constituents of rocks. Again, many more or less loosely-aggregated rocks have been permeated by siliceous solutions and converted into hard, unyielding masses. Thus, loose sand has been solidified into sandstone, while sandstone, in its turn, has been highly indurated and changed into quartz-rock. Another result of the circulation of such solutions has been the filling-up of cracks, fissures, and cavities of all shapes and sizes, in almost every kind of rock. Hence, quartz frequently appears in the form of ramifying veins and veinlets, and is one of the commonest minerals associated with ores in lodes. 4. As quartz resists decomposition and is the commonest of all rock-forming minerals, it enters conspicuously into the formation of a large number of sedimentary rocks. These, as we shall learn, are simply residual products—that is to say, they have been derived from the disintegration and degradation of pre-existing rock-masses; and quartz, in consequence of its superior durability, its great abundance, and wide distribution, naturally forms a dominant ingredient of conglomerates, greywackés, sandstones, etc.

In coarsely crystalline rocks, quartz, even when it shows no external crystalline form, is quite readily recognised by its other physical characters—namely, by its hardness, its uneven or conchoidal fracture, its vitreous lustre, and the absence of any trace of decomposition. In coarse-grained granite, for example, it appears like a kind of transparent cement, filling up the straggling spaces between the other mineral ingredients, which it thus seems to bind together. In certain other eruptive rocks, as in quartz-porphyry, pitchstone, etc., it often occurs as conspicuous, corroded, but occasionally well-formed crystals, disseminated through a groundmass of fine-grained materials (see Plate IV. 4). The best-developed quartz-crystals met with in eruptive rocks, however, are found in certain curious irregular cavities which frequently appear in granite. The walls of such cavities are usually lined with fine crystals of the several mineral constituents of the rock, amongst which hexagonal prisms and pyramids of quartz are commonly prominent (see Plate XI. 2).

In finely crystalline rocks, the presence of quartz can only be determined by microscopic examination. In thin slices it appears limpid, water-clear, and quite unaltered. It shows no trace of cleavage, but is traversed by numerous irregular cracks. The surface appears smooth, and neither bounding edges nor internal cracks are pronounced. When crystals of the mineral are present (as in quartz-porphyry), they usually show lozenge-shaped outlines with rounded angles. According to the thickness of the slice, and the direction of the section, the polarisation colours vary in intensity, being grey, white, yellow, orange, blue, or green.

Enclosures of other minerals are common in quartz. [In large crystals these are often visible to the naked eye (see Plate I. 2).] Under the microscope even the smallest granules of the quartz of eruptive rocks, such as granite, may appear crowded with inclusions of rutile, apatite, and other minerals. The quartz of granite also usually contains numerous minute fluid cavities, more or less irregularly disseminated through the mineral, while the quartz of pitchstones, rhyolites, and quartz-porphyries frequently encloses minute quantities of glass or stone (see Plate IV. 4).

Varieties of Quartz.—The chief phanerocrystalline varieties are the following:—*Rock-crystal*, water-clear; *Avanturine*, rock-crystal, abundantly spangled with enclosed scales of mica or other mineral; *Amethystine Quartz*, violet-coloured rock-crystal; *Smoky Quartz* includes dusty-brown to black (*Morion*) and paler brown to yellow (*Cairngorm*) rock-crystal; *Milky Quartz* is milk-white and nearly opaque, with a somewhat greasy lustre; *Common Quartz*, not transparent, white, but occasionally coloured, sometimes occurs with crystalline form, but is usually massive. The most important cryptocrystalline variety of quartz is **Chalcedony**. This is a secondary mineral, which may occur in almost any kind of siliceous rock. It frequently lines or fills vesicles, fissures, and other cavities in igneous rocks, and is common in metalliferous veins or lodes. It is translucent, and has a somewhat waxy lustre. The colour varies, the commoner kinds being white or grey, but brown or black, and yellowish-green and blue varieties are known. It frequently shows a banded structure, and often assumes nodular, mammillary, botryoidal, reniform, or stalactitic shapes, being obviously in such cases a deposition from aqueous solution. When a thin slice of a spherical concretion is seen under the microscope, chalcedony exhibits a finely fibrous radiating texture, and between crossed nicol prisms shows a black cross, which remains stationary while the slide is being rotated. Under chalcedony are included the following:—*Carnelian*, bright red, but sometimes yellowish; *Chrysoprase*, apple-green; *Plasma*, dark leek-green, but when spotted with carnelian known as *Heliotrope* or *Bloodstone*; *Agate*, a variegated chalcedony, the colours being either banded or in clouds, or due to visible impurities. In *Banded Agate* the layers are wavy or zigzag, or concentric and more or less spherical, according to the conditions of deposition, and the shape of the cavity occupied by the mineral (Plate I. 1). In *Clouded Agate* the variously coloured portions are irregularly distributed. When visible impurities in a chalcedony assume moss-like or dendritic shapes, we have the variety known as *Moss Agate*. *Onyx* is an agate in which the coloured layers occur in even planes; when one of these is dark brown, overlaid by a bluish-white layer, the mineral is used for cameos—the figure being carved in the white layer, while the dark layer serves for a background. *Sardonyx* is an onyx consisting of alternate layers of carnelian and opalescent chalcedony. *Jasper* is an impure chalcedony of various colours, red (due to ferric oxide) being the commonest. *Flint* is allied to chalcedony, consisting of cryptocrystalline silica, but rendered opaque owing to abundant impurities; it has a marked conchoidal fracture. *Chert* (including *Hornstone*) differs little from flint: the fracture is splintery rather than conchoidal. Flint and chert occur chiefly in calcareous rocks, in the form of nodules, layers, or irregular concretions.

Weathering of Quartz and Chalcedony.—While the crystallised varieties of quartz remain practically unaffected by the chemical action of percolating water, the cryptocrystalline and amorphous forms of that mineral are not so resistant, but frequently "weather" with a white crust.

Opal is an amorphous mineral (*i.e.* devoid both of external crystalline form and internal crystalline structure). It is composed of silica, with a variable proportion of water (usually from about 3 to 10 per cent.); the specific gravity of the mineral (1·9 to 2·3) is somewhat less than that of quartz, and the same is the case with the hardness (5·5 to 6·5). The texture is colloidal or jelly-like; and the lustre vitreous to resinous. The colour varies—it may be white, red, brown, yellow, green, or blue, and some kinds show a rich play of colours. Opal usually occurs in reniform, botryoidal, or stalactitic masses, occupying any irregular cavity in rocks. In all cases it is of secondary origin—that is, it has been subsequently introduced as a product of decomposition. Many varieties are recognised, among which the following may be mentioned: *Siliceous Sinter* or *Geyserite*, deposited from thermal waters, often loose and earthy; *Hyalite*, usually water-clear, colourless, but sometimes white or translucent—it occurs in the joints, fissures, and vesicular cavities of some basalts; *Noble* or *Precious Opal*, with a rich play of colours, met with in irregular cavities in trachyte, etc.; *Common Opal*, translucent, but showing no play of colours, occurs in veins, fissures, etc., in igneous rocks; *Semi-Opal* is less translucent than common opal; *Jasp-Opal* is red or brown in colour; *Menilite* is an opaque greyish or brown concretionary opal, occurring occasionally in argillaceous rocks.

Specular Iron or Hæmatite, oxide of iron (Fe_2O_3), crystallises in hexagonal forms (which are commonly combinations of rhombohedra and scalenohedra). It has a hardness of 5·5 to 6·5, and a specific gravity of 5·19 to 5·28; crystals are bluish iron-grey in colour, while fibrous forms are usually brownish-red. The mineral yields a red powder when rubbed with a steel file. This red streak and the absence of magnetism distinguish specular iron from magnetite. It occurs both crystalline and massive. The crystalline variety is common in veins, and is often accompanied by magnetite. Not infrequently it occurs as an ingredient of granite, syenite, gneiss, mica-schist, phyllite, etc. It is met with in many minerals as a microscopic inclusion (*endomorph*), in the form of minute filmy plates or scales, the presence of which affects the colour of the including mineral (*perimorph*), and often imparts to it a kind of pearly or submetallic glimmer or iridescence. Now and again it has been developed in limestones at or near their point of contact with eruptive rocks. It occurs as a sublimation-product in volcanic regions.

The more compact or cryptocrystalline varieties of hæmatite usually occur as veins, irregular beds, and masses. *Kidney-ore* is the name given to nodules and nodular masses, which often consist of concentric coats having a radiating fibrous structure. Hæmatite frequently occurs in decomposing igneous rocks as an alteration-product of ferromagnesian minerals, and it often coats the faces of joints in these and other ferriferous rocks. It is probable, however, that the ferruginous mineral commonly seen on joint-faces is in many cases not true hæmatite, but *Hydro-hæmatite* or *Turgite*, which contains a small percentage of water—only 5 per cent. In other respects it is so closely similar to hæmatite that it can only be differentiated from the latter by analysis.

Ilmenite is an iron-black mineral, with metallic or submetallic lustre, having the composition of $FeTiO_3$, and crystallising in rhombohedral forms. It has a hardness of 5 to 6, a specific gravity of 4·56 to 5·21, and the streak is black to reddish-brown. It is practically infusible before the blowpipe, and is not attacked by acids.

This mineral occurs as massive aggregates in certain plutonic rocks, especially in gabbros. It is met with as an accessory ingredient in many eruptive rocks (granite, syenite, gabbro, basalt, dolerite, andesite), and also as a constituent of some crystalline schists.

As a rock-constituent ilmenite appears under the microscope either in the form of rhombohedral crystals or as irregular grains and patches, which are often hard or impossible to distinguish from similar aggregates of magnetite, being like these, black, opaque, and showing a metallic lustre. The mineral is often altered round its margins or even throughout into a dull greyish-white opaque substance known as *Leucoxene* (see under *Titanite*).

Magnetite (Fe_3O_4) crystallises usually in the form of octahedra or dodecahedra. It has a hardness of 5·5 to 6·5, and a specific gravity of 4·9 to 5·2. Its strong magnetism, black streak, and frequent occurrence in octahedra, distinguish magnetite from all other common minerals. It is iron-grey or black, like ilmenite, but hardly so infusible, while it is soluble in hydrochloric acid. Ilmenite, again, weathers with a greyish crust (leucoxene) ; magnetite, on the other hand, weathers brown (limonite). Magnetite is a widely distributed rock-former, occurring as large and small crystals in chlorite-schist and other foliated rocks. Now and again it is found associated with such rocks in the form of massive beds with a granular structure, throughout which chromite, ilmenite, pyrite, chalcopyrite, etc., are often abundantly disseminated. While common in acid igneous rocks, it is a still more frequent (usually microscopic) constituent of basic igneous rocks. Occasionally in gabbros it occurs as massive aggregates. It is met with also as a secondary mineral in many eruptive rocks—a product of the alteration of such ferromagnesian constituents as olivine, augite, hornblende, and biotite. Not being readily decomposed, magnetite often appears in alluvial sands derived from the disintegration of basic eruptive rocks, etc.

Limonite ($2Fe_2O_3+3H_2O$) occurs as fibrous aggregates, assuming nodular, stalactitic, or botryoidal forms, or as large irregular masses. Its hardness is 5 or thereabout, but earthy varieties are softer—the specific gravity = 3·4 to 3·95. It is brown or yellowish-brown, and has a yellow-brown streak. As a rock-constituent it is always a product of alteration—derived from the decomposition of minerals which contain iron. Limonite is itself amorphous, but is often met with filling the moulds formerly occupied by other minerals, and thus assuming their crystalline form (*pseudomorphs*).

Rutile ($TiO2$) as a rock-former occurs usually as minute dark brown or reddish grains, pointed prisms, and knee-shaped (Fig. 2) or heart-shaped twin-crystals, belonging to the tetragonal system. It is met with in various schistose rocks (gneiss, mica-schist, phyllite, eclogite, etc.). Needle-like crystals are also common in clay-slate and greywacké, and are frequent enclosures in such minerals as rock-crystal (Plate I. 2) and mica. As rutile is not readily attacked by the various agents of decomposition, it often survives the destruction of the rocks of which it once formed a part, and is thus of common occurrence as grains and pebbles in sand and gravel. It is relatively hard and heavy; its hardness being 6 to 6·5, and its specific gravity 4·2 to 4·3. It is infusible before the blowpipe, and insoluble in acids.

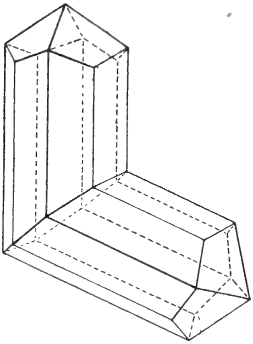


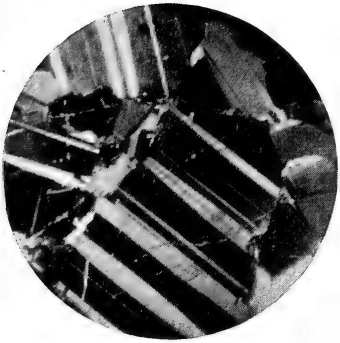
FIG. 2.—CRYSTAL OF RUTILE.
A knee-shaped (geniculate) twin.

Zircon ($ZrSiO_4$) as a rock-former can rarely be distinguished by the naked eye. It appears mostly in the form of small brown crystals (tetragonal), enclosed in other minerals. Although only sparingly present, it has a wide distribution, occurring in eruptive rocks of all kinds (but only rarely in the basic kinds), as well as in crystalline schists, especially gneiss. Larger crystals are found in some kinds of syenite. Like magnetite and rutile, zircon is not readily decomposed, and is thus often met with in quartz sands which have been derived from the disintegration of rocks in which the mineral occurs as a primary constituent. The mineral is harder and heavier than rutile—the hardness being 7·5 and the specific gravity 4·5 to 4·7. It is infusible before the blowpipe, and soluble with difficulty and incompletely in heated sulphuric acid. Fine, clear-coloured varieties (*Jacynth* and *Jargoon*) are valued as gems.

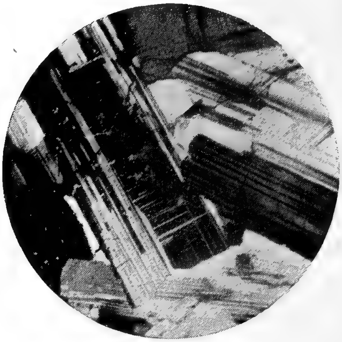
Spinelloids.—These minerals crystallise in isometric forms, and are all (excepting chromite) very hard. They are not attacked by acids. **Spinel** ($MgAl_2O_4$) has a hardness of 8, and a specific gravity of 3·5 to 4·1. Its cleavage is imperfect. It is infusible, and not readily attacked by acids. It varies in colour—red, yellow, blue, green, and black varieties being known. It occurs in some schists and metamorphosed limestones and dolomites. [The beautiful coloured transparent varieties are in some request as gems—the red crystals being known as "spinel-ruby" or "balas-ruby"; the golden-yellow or orange-red as "rubicelle"; and the violet as "almandine-spinel."] *Pleonaste* is a greenish-black to black magnesia-iron spinel, occurring in the ejected limestone-blocks of Monte Somma (Vesuvius), and met with occasionally in marble and in the *xenoliths* or foreign rock-fragments enclosed in basalts, andesites, etc. *Picotite* is a dark brown to black chrome spinel, often present in eruptive rocks which are rich in olivine (peridotites). *Chromite* ($FeCr_2O_4$) is a dark brown to black spinelloid, of considerable commercial importance. Its specific gravity (4·5 to 4·8) exceeds that of spinel, but its hardness (5·5) is considerably less. This is the only mineral from which salts of chromium are obtained for the production of chrome-yellow and chrome-green. As a rock-constituent, it is a common and often abundant ingredient of olivine-rocks and serpentine.

PLATE II.

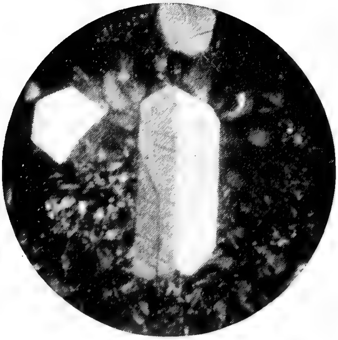
Microscopic Structure of Minerals and Rocks.



1.



2.

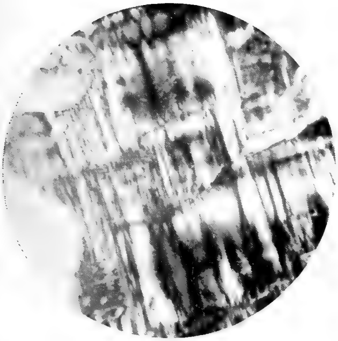


3.

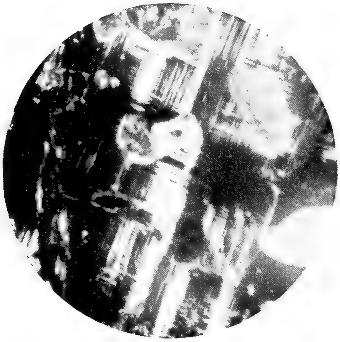
4.

1. Plagioclase showing Albite-twinning. Gabbro. Nicols crossed.
2. Plagioclase showing Albite- and Pericline-twinning. Diorite. Nicols crossed.
3. Twinned crystal of Sanidine (Orthoclase) in pseudo-spherulitic groundmass. Rhyolite. Nicols crossed.
4. Crystals of Sanidine (Orthoclase) showing Carlsbad-twinning and fluxional arrangement. Trachyte. Nicols crossed.

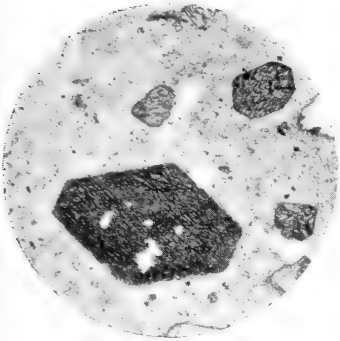
MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS.



1.



2.



3.

4.

1. Microcline with spindle-shaped twin lamellæ. Granite. Nicols crossed.
2. Microcline with trellis-structure; shows inclusions of Quartz and weathered Orthoclase. Granite. Nicols crossed.
3. Euhedral or Idiomorphic crystal of Hornblende in transverse section, with characteristic outlines and cleavage. Above are crystals of Augite. Andesite.
4. Anhedral or Allotriomorphic Hornblende, with characteristic cross-cleavage. Basal sections of Biotite (below) without cleavage. Dusty Felspar (above), enclosing two small prisms of Apatite. Granite.

[*Between pages* 8 *and* 9.

Corundum (Al_2O_3) crystallises in hexagonal prisms and pyramids, but is often massive. It is a very hard mineral (9 in the scale), and has a high specific gravity (3·9 to 4). It occurs sparingly in some granites, syenites, schists, metamorphosed limestones, and basalts. The beautiful clear-coloured varieties (Ruby and Sapphire) are highly valued as gems. As a rock-ingredient corundum is of little importance; sometimes, however, it occurs in considerable masses. *Emery* (an intimate mixture of corundum and magnetite and hæmatite) occurs in veins and layers in crystalline schists.

Pyrolusite, Psilomelane, and **Wad** (oxides of manganese) are also unimportant rock-formers, but they often appear (particularly psilomelane) as thin films coating the walls of cracks and fissures or the surfaces of bedding-planes in various kinds of rock. The films often assume plant-like forms ("dendritic markings," see Plate XXVIII.). The earthy varieties of these oxides occasionally form bedded masses.

II. SILICATES

FELSPAR GROUP

Felspar is a general term for a number of closely related minerals which play a very important rôle as rock-formers. They are the chief constituents of most eruptive rocks, and are met with likewise more or less abundantly in many crystalline schists. They vary in colour, but are usually grey, white, or reddish; occasionally, however, they show yellow, green, or blue tints. As rock-constituents they frequently assume the form of tabular crystals, or appear as long rods or rectangular lath-shaped bodies. All are characterised by two well-marked sets of cleavage-planes (at, or nearly at, right angles) which show usually a glassy or pearly lustre; further, all have approximately the same hardness (6 to 7), and specific gravity (2·54 to 2·76). Chemically, they are silicates of aluminium with either potassium, sodium, or calcium, or several of these together. Hence we have potash felspar, soda felspar, lime felspar, soda-lime felspar, etc. These felspars so closely resemble each other that it is often hard or even impossible to distinguish one from another by the unassisted eye. This, of course, is especially the case when the crystals are small. Usually, however, the particular class or series to which a felspar belongs can be determined by examination in thin slices under the microscope. Two series of felspars are recognised—one of these crystallising in monoclinic and the other in triclinic forms. The monoclinic series includes Orthoclase and Sanidine, while the triclinic class is represented by Microcline, Anorthoclase, and Plagioclase—the last-named forming a group of felspars which are all more or less closely related, and often hardly to be distinguished from each other without careful microscopical or chemical examination. As a group they are more or less readily differentiated from the monoclinic felspars by the inclination of their cleavage-planes—in the monoclinic felspars these planes being directed at right angles to each other, while in the triclinic group referred to they are not at right angles. Hence we have two series of felspars—namely, (*a*) Orthoclase, with rectangular cleavage, and (*b*) Plagioclase, with oblique cleavage.

If felspars always assumed their external crystalline form and were of sufficient size, it would not be hard to distinguish between orthoclase and plagioclase. As rock-constituents, however, they are often so unsymmetric in shape, or occur as granules so small in size, that the geologist must have recourse to other differentiating characters to distinguish between one felspar and another. Under the microscope, the plagioclase felspars can usually be recognised by their "multiple twinning." A crystal or crystalline granule having this structure appears as if it were composed of a series of parallel plates or lamellæ. Twinning is best seen in polarised light—each plate being differently coloured from its neighbours, so that a section of the mineral, if cut in the proper direction, exhibits a banded or striped appearance (Plate II. 1, 2). As the mineral constituents of a crystalline igneous rock usually lie at different angles and in different directions, it does not often happen that the structure referred to is not revealed by one or more of the individual plagioclase crystals, which are exposed in the field of vision under a microscope. Even when the minerals are arranged in approximately parallel layers, as in the case of schistose rocks, it is always possible to cut sections both in the direction of, and across, or at any angle to, the planes of foliation. Not infrequently the twinned structure can be seen by the naked eye or with the aid of a pocket-lens, when the felspars are fresh and not too small. The structure is revealed by the appearance of fine parallel lines, with which the crystals are ruled or striated—the lines marking, of course, the junction of separate twin lamellæ. The twinning of orthoclase felspars is

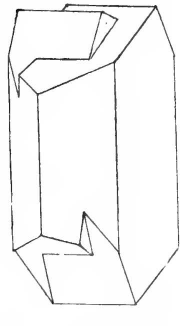


FIG. 3. — CRYSTAL OF ORTHOCLASE: CARLSBAD TWIN.

simple (Fig. 3), so that a section cut in the right direction shows in polarised light only two differently tinted bands (see Plate II. 3, 4). When the mineral is not twinned, or when the section is cut parallel to the twinning plane, orthoclase felspars polarise in one uniform colour. The following are the more important felspars :—

Orthoclase (monoclinic potash felspar, with high percentage of silica). This mineral is usually white, grey, or reddish. It is not attacked by ordinary acids, but is decomposed by hydrofluoric acid, and fuses before the blowpipe with difficulty on thin edges. As a rock-former it occurs most frequently as imperfect crystals, or irregular crystalline aggregates. In certain igneous rocks, however (as in quartz-porphyry), it appears as conspicuous and sometimes well-formed crystals disseminated among the finer grained constituents of the mass. Fine crystals of orthoclase often occur in drusy cavities and veins in granite, and now and again in fissures traversing crystalline schistose rocks. The mineral is an essential ingredient of many eruptive rocks (granite, quartz-porphyry, syenite, rhyolite, phonolite, trachyte, etc.). It is readily distinguished from quartz by its hardness, cleavage, twinning, and frequent turbidity—due to gradual alteration of the mineral into kaolin.

Sanidine is a glassy clear variety of orthoclase, usually much cracked, and often crowded with inclusions. It is the type of orthoclase which characterises the younger volcanic rocks—rhyolite, trachyte, phonolite, etc., and frequently assumes the form of tabular crystals (see Plate II. 3, 4).

Adularia is another clear, transparent orthoclase, found in the irregular drusy cavities of some gneisses, and in fissures in schistose rocks.

Microcline (triclinic potash felspar) has the same chemical composition as orthoclase, from which it can hardly be distinguished without examination under the microscope. It is a frequent constituent of granite, appearing often in well-developed forms in the drusy cavities, and the coarsely crystalline veins associated with that rock. It occurs also in certain syenites and other eruptive rocks of deep-seated origin, and is occasionally present in gneiss. Although it thus frequently accompanies orthoclase proper, it has not yet been met with in rocks that contain the glassy variety of that mineral—sanidine. Under the microscope, microcline usually shows a polysynthetic structure, due to the presence of minute spindle-shaped twin lamellæ, so arranged that, when the section is cut in a particular direction, it has in polarised light a peculiar cross-hatched appearance (see Plate III. 1, 2).

Anorthoclase (triclinic soda-potash felspar) shows much the same structure under the microscope as microcline, but usually on an exceedingly minute scale. It occurs in the form of phenocrysts with rhombic outlines in a well-known igneous rock (rhombenporphyr) met with in S. Norway, between Christiania and Langesundfjord.

The potash felspars generally weather readily into kaolin. Not infrequently, however, they are transformed into other minerals—muscovite (potash mica) often replacing orthoclase.

The **Plagioclase** felspars sometimes occur in crystalline masses. As rock-formers, however, they usually appear as elongate tabular crystals, not infrequently grouped in bundles or forming radiating aggregates, or they may be mere crystalline granules. They form a series, of which *Albite* (sodium-aluminium silicate) and *Anorthite* (calcium-aluminium silicate) are the two extremes. The intermediate forms are regarded as isomorphous mixtures of these two silicates in various proportions, as shown in the following table, where Ab stands for albite, and An for anorthite :—

Albite (soda felspar).

Oligoclase : mixture of Ab and An—the former predominating.

Andesine : mixture of Ab and An in nearly equal proportions—Ab slightly predominating.

Labradorite : mixture of Ab and An—the latter slightly predominating.

Bytownite : mixture of Ab and An—the latter largely predominating.

Anorthite (lime felspar).

The silica percentage ranges from 43·16 in anorthite to 68·68 in albite. Plagioclase felspars fuse with difficulty before the blowpipe. Anorthite is decomposed by hydrochloric acid with gelatinisation, while albite resists ordinary acids—the intermediate varieties becoming more readily affected the nearer they approach in composition to anorthite. All are subject more or less readily to alteration, being transformed especially into such minerals as kaolin, sericite (a variety of muscovite), and epidote. *Saussurite* is the name given to an altered plagioclase which often occurs in gabbro. It is fine-grained to compact, grey, ash-grey, or greenish-white, shimmering or dull, and translucent on thin edges.

Well-developed and more or less perfect crystals of plagioclase often occur in the drusy cavities of eruptive rocks;

in fissures in crystalline schists; and in blocks ejected from volcanoes. The plagioclase felspars are among the most important rock-formers, occurring as primary constituents of a large number of eruptive rocks both as macroscopic and microscopic individuals. They have also a wide distribution amongst the crystalline schists. The felspars (monoclinic and triclinic alike), being readily weathered and decomposed, are met with only now and then as ingredients of derivative rocks; they are not uncommon, however, in greywackés—especially oligoclase.

A few notes on the individual plagioclase felspars may be added :—

Albite (soda felspar) : usually white ; resembles orthoclase, from which it may be distinguished by its greater specific gravity (orthoclase, 2·54 to 2·58 ; albite, 2·61 to 2·64) and the character of its twinning. Although albite frequently appears as lamellar intergrowths in orthoclase and microcline (= *microperthite*), yet it cannot be described as an important constituent of igneous rocks. It is a common ingredient, however, of certain crystalline schists. Now and again it occurs as a "contact mineral" in argillaceous and calcareous rocks, near their junction or contact with intrusive eruptive rocks.

Oligoclase is a common constituent of many eruptive rocks, especially of those in which quartz or orthoclase, or both together, occur as important ingredients, as in syenite and granite. It is present likewise in some diorites, and in many of the porphyries which are associated with plutonic rocks ; not infrequently also in trachytes and andesites ; and often in gneiss.

Andesine is a frequent constituent of certain eruptive rocks, such as syenite, tonalite, andesite, dolerite, and basalt.

Labradorite is a common constituent of basic eruptive rocks (gabbros, norites, basalts, diorites), and occurs in large masses in certain plutonic rocks, where it frequently shows a very fine play of colours, due to the interposition along the cleavage-planes of minute scales or platy inclusions.

Bytownite occurs not uncommonly in andesites, basalts, and other basic eruptive rocks.

Anorthite (lime felspar) occurs not infrequently as a constituent of many basic igneous rocks, as in some diorites, gabbros, peridotites, basalts, and, less frequently, in certain andesites. It is also an occasional constituent of metamorphic rocks. Fine glassy crystals of this felspar occur in the drusy cavities of limestone-blocks which have been ejected from Vesuvius.

THE FELSPATHOID GROUP

The felspathoids (*Leucite, Nepheline, Sodalite, Haüyne, and*

Nosean) are akin to the felspars in chemical composition, and play much the same part as rock-formers. They are not nearly so important, however, the rocks of which they are characteristic constituents being much less widely distributed. They are restricted, indeed, to a few igneous rocks mostly belonging to a late geological period. They never occur as ingredients of the crystalline schists.

Leucite (silicate of potassium and aluminium) generally appears in the form of more or less well-defined single crystals, having the shape of icositetrahedra (24-faced trapezohedra). In cross-sections the larger crystals often yield six-sided or eight-sided contours, while the smaller crystals are rounded. The mineral has a hardness of 5·5 to 6, and a specific gravity of 2·45 to 2·50. If pure, it is transparent and colourless, but most frequently, owing to the presence of impurities, it appears ash-grey or greyish-yellow, and then it is only translucent on thin edges. It is almost infusible before the blowpipe ; when reduced to a powder it readily dissolves in hydrochloric acid, with separation of pulverulent silica. Under the microscope, leucite usually shows abundant symmetrically arranged inclusions of glass, gas pores, and minute microlites, grains, etc., of such minerals as felspar, augite, and magnetite. Between crossed nicol-prisms it exhibits weak, anomalous double refraction—yielding dark grey colours—the crystals being traversed by intersecting alternately light and dark twin lamellæ. This structure, however, is not seen in the smaller crystals, which are usually isotropic. The mineral is readily altered in nature, becoming white and opaque as it is changed into zeolites or kaolin. Probably its proneness to alteration is the reason why it seldom occurs in very old igneous rocks. It is a macroscopic and microscopic constituent of certain basic Vesuvian lavas. Similar rocks occur elsewhere in Italy, and in a few other countries.

Nepheline is essentially a sodium-aluminium silicate, but contains some potassium. Hardness, 5·5 to 6 ; specific gravity, 2·58 to 2·64. As a rock-constituent it appears in the form of somewhat stout hexagonal prisms with a glassy lustre, and is either water-clear or white. Its hardness is similar to that of leucite. It is fusible before the blowpipe with some difficulty ; and gelatinises with acids. It is an essential constituent of phonolite and nepheline-basalt, and very commonly occurs in rocks which contain leucite as an essential ingredient. Like leucite, the mineral is unstable and thus frequently altered into fibrous zeolites or muscovite. A dull grey variety of nepheline, with a greasy lustre, and known as *Elæolite*, is a conspicuous component of certain syenites.

Sodalite is another sodium-aluminium silicate, but it contains chlorine. It crystallises in isometric forms (dodecahedra), and has a hardness of 5·5, and a specific gravity of 2·2 to 2·4. It fuses to a colourless glass; and gelatinises with acids. It is a microscopic constituent of certain trachytes and phonolites, occasionally appearing as well-defined crystals in the vesicular cavities and fissures of such rocks. Its common alteration-products are fibrous zeolites. A compact blue variety, with a greasy lustre is a notable ingredient of elæolite-syenite.

Haüyne and **Nosean** are isomorphous mixtures of sodium-aluminium silicate and calcium-aluminium silicate, both with sulphur. Hardness, 5·5; specific gravity, 2·28 to 2·5. Both minerals are fusible before the blowpipe; and both are decomposed by acids. They crystallise in isometric forms. The larger individuals often show crystalline contours, giving in microscopic sections more or less imperfect hexagonal or quadrangular figures. Not infrequently the crystals present the appearance of having been corroded. The minerals are hard to distinguish from each other, but haüyne is usually blue or bluish-green, while nosean is generally grey, although it may be greenish, brown, red, or yellow. Microscopic examination shows that they are usually crowded with inclusions. Both minerals are fusible before the blowpipe and gelatinise with hydrochloric acid. They occur as macroscopic and microscopic constituents of certain igneous rocks that are rich in alkalies, such as phonolite. They are thus frequent associates of leucite and nepheline. Both are apt to be altered into fibrous zeolites.

CHAPTER II

ROCK-FORMING MINERALS—*continued*

Silicates — Amphibole and Pyroxene Group ; Mica Group ; Olivine Group ; Chlorite Group ; Talc Group ; Epidote Group ; Garnet Group ; Tourmaline Group ; Titanite Group ; Andalusite Group ; Zeolite Group ; Kaolinite Group. Haloids—Fluorite and Rock-Salt. Sulphides—Pyrite, Pyrrhotite, and Marcasite. Carbonates—Calcite, Aragonite, Dolomite, and Siderite. Sulphates—Anhydrite, Gypsum, and Barytes. Phosphates—Apatite, etc. Elements—Graphite.

THE AMPHIBOLE AND PYROXENE GROUP

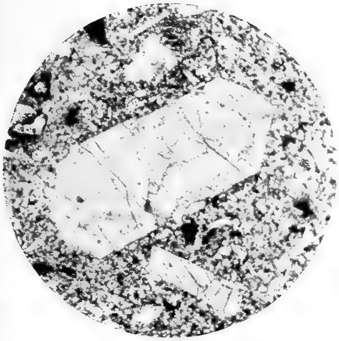
THE **Amphiboles** described here are calcium-magnesium silicates ; others not referred to contain soda. Some are rich in aluminium and iron, while others contain little or no trace of either. When crystallised they appear as prisms : but they show a marked tendency to assume fibrous and radiated forms. Their specific gravity ranges from 2·9 to 3·5, and their hardness is between 5 and 6. They are usually fusible, more particularly when rich in iron.

Amphiboles crystallise both in monoclinic and orthorhombic forms, but only the former are important rock-formers. The *monoclinic non-aluminous amphiboles* are usually lighter in colour than those rich in aluminium and iron. The most commonly occurring representatives of the non-aluminous class are Tremolite and Actinolite.

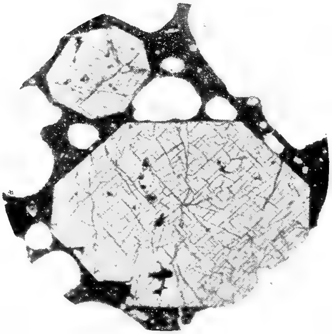
Tremolite is white, grey, or light green in colour, and occurs usually in the form of long blade-shaped crystals, striated longitudinally : or it assumes the appearance of thin fibrous crystals radiating from a centre. The crystals have a pearly or silky lustre. This mineral is a constituent of some schistose rocks ; it occurs not uncommonly in crystalline limestone (marble) and dolomite near their point of contact with plutonic rocks. Now and again it is met with as an alteration-product in olivine-rocks and serpentine. **Actinolite** differs from tremolite in containing a

PLATE IV.

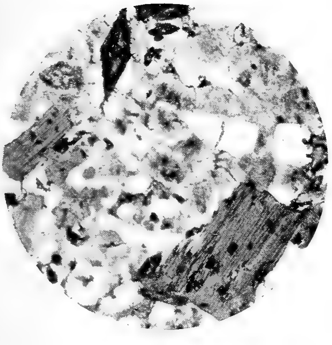
MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS.



1.



2.



3.

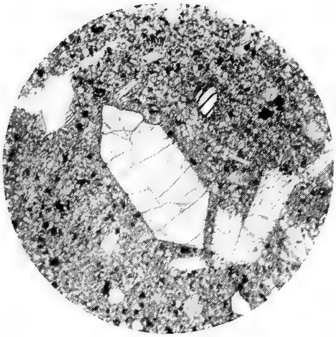
4.

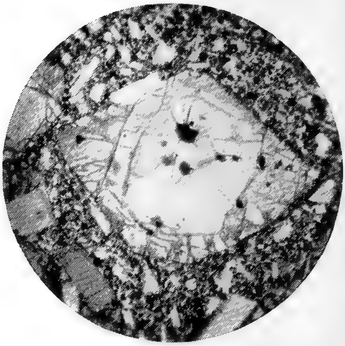
1. Euhedral or Idiomorphic crystal of Augite with prismatic cleavage. Basalt.
2. Crystals of Augite in transverse section, with characteristic outlines and cleavage. Vesicular Basalt.
3. Rectangular crystals of Biotite with parallel cleavage; dusty decomposing Felspar, and clear grains of Quartz. The lozenge-shaped crystal (above) is Sphene. Granitite.
4. Corroded crystal of Quartz with inclusions of glass. Pitchstone.

[*To face page* 16.

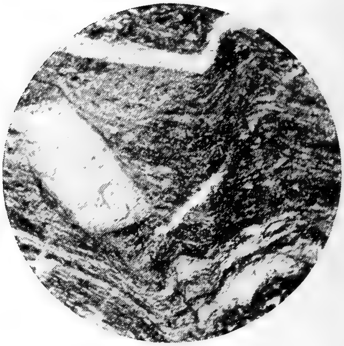
PLATE V.

MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS.


1.


2.


3.


4.

1. Idiomorphic Olivine in longitudinal section, with transverse cracks and imperfect cleavage. Basalt.
2. Crystal of Olivine with incipient serpentinization along the cracks and borders. Basalt.
3. Crystals of Chiastolite (Andalusite) with inclusions. Slate.
4. Chiastolite in contorted Slate.

[*To face page* 17.

considerable percentage of iron ; hence it is generally light or dark green in colour. It usually occurs as long thin columnar crystals and radiate aggregates. It is a common ingredient of many crystalline schists, where it is frequently associated with talc, chlorite, and epidote. In eruptive rocks (as in saussurite-gabbro) it is often met with as an alteration-product.

Tremolite and actinolite sometimes assume forms so fibrous that they can be readily separated into thin, soft, cotton-like, or silky threads, and are then known as **Amianthus** or **Asbestos**. The fibres are often matted together so as to form felt-like substances, termed "mountain-leather," "mountain-cork," etc. Most of the asbestos of commerce, however, is not amphibole, but fibrous serpentine (chrysotile).

Of the *monoclinic aluminous amphiboles*, by far the most important is **Hornblende.** This mineral has much the same composition as actinolite, but contains a notable percentage of alumina. Two varieties are recognised—namely, **Common Hornblende** and **Basaltic Hornblende.** The former is dark leek-green to black, and occurs generally as long prismatic crystals, but sometimes as blade-like, fibrous, radiating aggregates. It is opaque in reflected light, but usually green in transmitted light. It is an essential constituent of many plutonic rocks (syenite, diorite, hornblendic granite), occurring now and again as an accessory ingredient in gabbro. It is a frequent constituent of crystalline schists (amphibole-schist, hornblende-gneiss). It commonly alters to chlorite or epidote, or may be still further broken up by weathering, and reduced to the condition of a ferruginous clay.

Basaltic Hornblende is generally brownish-black to pitch-black, but when viewed in thin sections it usually shows a deep brown or reddish-brown colour. The crystals are commonly short, stout prisms, and are frequently well formed (see Plate III. 3). The mineral occurs as a macroscopic and microscopic ingredient of certain trachytes, andesites, and basalts—the larger crystals often showing corroded blackened borders—the result of magmatic resorption.

The only other monoclinic amphibole that need be mentioned is **Smaragdite**—a peculiar grass-green fibrous lamellar form, approaching actinolite in composition, but containing a considerable percentage of alumina. It occurs in eclogite, where it forms parallel growths with omphacite—a similar green pyroxene mineral.

The **Pyroxenes** have much the same chemical composition, hardness, and specific gravity as the amphiboles, and crystallise like them in monoclinic and orthorhombic forms. They differ amongst themselves as regards fusibility—those containing much iron being usually more fusible than the less ferriferous varieties. The monoclinic forms are divisible, like the corresponding amphiboles, into non-aluminous and aluminous types. The *non-aluminous pyroxenes* are mostly light-coloured—white or, more commonly, some pale shade of green. They occur chiefly in crystalline schists and in crystalline limestones and marbles, but are not such important rock-formers as the corresponding light-coloured amphiboles. Their alteration-products are usually talc or serpentine. Of the *aluminous pyroxenes* the most notable is **Augite** (see Plate IV. 1, 2); it crystallises in prismatic forms, which are often twinned. As rock-constituents the crystals frequently have their edges and angles rounded off. Augite is dark brown to black, but in thin sections may be almost colourless or show various shades of brown or yellow, and sometimes of green. It is often altered into an aggregate of chlorite, scattered through which may be minute granules of epidote, calcite, and quartz; or it may be still further changed to a mixture of limonite, quartz, and carbonates. Sometimes it is replaced by biotite, epidote, calcite, etc. It is an essential constituent of such basic rocks as basalt, dolerite, etc., but occurs as an accessory ingredient of many other eruptive rocks. **Diallage** is a brownish, grey, or greenish variety of augite, which rarely assumes a crystalline form, and has a lamellar or foliated structure. Numerous platy inclusions occur along the cleavage-planes, so that the mineral exhibits a submetallic lustre on broken surfaces. It is an essential constituent of gabbro, and occurs also as an occasional ingredient of serpentine and olivine-rocks; but appears never to be met with in effusive igneous rocks (lavas).

Omphacite is a bright green pyroxene occurring in granular and lamellar aggregates, and associated with smaragdite and red garnet in the rock known as eclogite.

The *orthorhombic pyroxenes* (hardness, 4 to 6; specific gravity, 3 to 3·5) play a more important rôle as rock-formers than the orthorhombic amphiboles. There are three types recognised—namely, *Enstatite*, *Bronzite*, and *Hypersthene*—but they seem to be varieties of one and the same species. **Enstatite** is a silicate of magnesium with a small percentage of iron. It is greenish-white usually, but sometimes darker coloured. It occurs most frequently in gabbros and rocks rich in olivine, generally in the form of aggregates, grains, and irregular masses. Better formed crystals have been met with in certain andesites and quartz-porphyries. **Bronzite** and **Hypersthene** have a chemical composition similar to that of enstatite, but contain a larger percentage of iron. Owing to the occurrence of abundant platy inclusions, bronzite yields a semi-metallic lustre on broken surfaces. Hypersthene is still richer in inclusions, and shows reddish copper-coloured reflections due to the interposition of numerous minute dark brown lamellæ. Bronzite is usually dark brown to reddish-brown, but sometimes yellowish or greenish; while hypersthene is much darker—the shades ranging from very dark green or dark brown to greenish-black and pitch-black. The two minerals have much the same habitat as enstatite, occurring frequently in gabbros, peridotites, and serpentines, generally without crystal outlines; while well-formed crystals are met with in some andesites and trachytes. It is by their behaviour in polarised light that geologists are able to distinguish between these orthorhombic pyroxenes. They are all pleochroic, and show a distinct change of colour when rotated on the microscope stage above the polariser. The pleochroism seems to increase with the increase of iron—the change of colour being feebler in enstatite and bronzite than in hypersthene. The rhombic pyroxenes containing little iron tend to be altered into yellowish-green fibrous serpentinous products termed *Bastite*.

The two most important members of the amphibole and pyroxene group are undoubtedly hornblende and augite, and as these minerals are often hard to distinguish, it may be useful to add a few notes on the characters by which they can be recognised:—

First, as regards habitat, the rule is that **Common Hornblende** most frequently occurs in rocks containing a considerable percentage of silica, and is thus often associated with quartz and highly silicated felspars, as orthoclase, albite, oligoclase. **Basaltic Hornblende,** on the other hand, occurs as an accessory ingredient chiefly in basic and intermediate eruptive rocks, as in many basalts, andesites, and trachytes. **Augite** is an essential constituent of basalts, and dolerites, and a common ingredient of some trachytes, andesites, etc.; only very rarely a pale augite has been met with in granite. So that we may say the home of common hornblende is chiefly in acid plutonic rocks and crystalline schists; while basaltic hornblende and augite are confined mostly to eruptive rocks not rich in silica.

In thin slices under the microscope it is generally easy to distinguish between hornblende and augite. The faces of the unit prism in hornblende are inclined to each other at an angle of 124° 30′, while in augite the corresponding angles are 87° 6′, or very nearly a right angle. The cleavage-planes being in the direction of these faces, it is obvious that those of augite must intersect at nearly 90°, while the angles between the two directions of cleavage in hornblende, in transverse sections of the crystal, will be 124° 30′ and 55° 30′ (see Plates III., IV.). The cleavage in hornblende is usually more marked than in augite. Again, hornblende is very distinctly pleochroic, while in augite the change of colour is usually feeble, and often altogether wanting.

The Mica Group

The micas, as rock-formers, mostly occur as thin plates and scales, the surfaces of which show a pearly to submetallic lustre. Usually these plates are irregular in shape, but now and again they are six-sided. The micas, however, are really monoclinic with pseudo-hexagonal symmetry. The cleavage is perfect, all micas being readily split up into exceedingly thin, transparent, and elastic leaflets. They are all rather soft (2·5 to 4 in the scale), and the specific gravity ranges from 2·7 to 3. They are essentially silicates of aluminium and potassium (or sodium), some kinds containing magnesium and iron. Only two micas are important rock-formers, namely, the brown to black **Biotite** or ferromagnesian mica, and the silver-white **Muscovite** or potash mica. They are essential constituents of many schistose rocks and of granite, and are met with in a large number of eruptive rocks of all ages. Soft, non-elastic scales of mica are also of common occurrence in many derivative rocks, particularly in fissile sandstones.

Biotite (ferromagnesian mica) is usually dark brown to black, but green and red varieties are known. It is decomposed by strong sulphuric acid; and in nature alters readily to chlorite, with separation of iron-oxide. Not infrequently, however, biotite becomes pale through loss of iron, and then assumes a golden yellow to silver-grey colour, thus sometimes closely resembling muscovite. It is a primary or original constituent of granites, rhyolites, some syenites and diorites, trachytes, etc. In effusive rocks the scales often show blackened borders, which, as in the case of basaltic hornblende, appear to be due to the corrosive action of the igneous magma. Biotite occurs also in certain schistose rocks. Being a less durable mineral than muscovite, it is not so often met with in sedimentary rocks. In thin rock-sections under the microscope, biotite, if cut at right angles to its vertical axis (or, in other words, if the slice be parallel to the cleavage-planes), appears deep brown or deep green to black, and shows little or no change of colour when rotated above the polariser. But when the section cuts across the cleavage-planes, which then appear as a series of parallel lines traversing the mica, as shown in Plate IV. 3, and the stage of the microscope is rotated, the change of colour is strongly pronounced. The polarisation colours are very brilliant in sections showing cleavage, and cut thin enough. Inclusions are frequently numerous, mostly of apatite and magnetite, and less commonly of zircon and rutile.

Muscovite (potash mica) is sometimes colourless, but usually pale-coloured or silvery; occasionally, however, it assumes a pale shade of brown or green. It fuses on thin edges to a grey glass or white enamel, but is not attacked by acids, and as a rock-constituent is not so readily altered as biotite. As a primary rock-former its chief habitats are the crystalline schistose rocks (gneiss, mica-schist, phyllite), and the granites. It never occurs as an original constituent in any igneous rocks save granite, certain quartz-porphyries, and syenites. Being a mineral not readily decomposed, it frequently appears in the form of soft, worn-looking, non-elastic scales in sedimentary rocks of many kinds. Although muscovite has no great range as a primary constituent of crystalline eruptive rocks, it occurs in many as a secondary ingredient—the product of the alteration of silicates rich in alumina. Thus it often replaces such minerals as andalusite, felspar, nepheline, etc. Seen in thin sections under the microscope, muscovite is colourless or very faintly yellowish or light green. It shows no change of colour, or at most only a slight difference in the intensity of the colour, when rotated above the polariser. It polarises, however, more brilliantly than biotite. Inclusions are few.

Although the micas, as rock-formers, occur most frequently in the form of scales, flakes, or plates of relatively small size, they now and again appear as large rough prisms, often tapering to a point—as, for example, in limestones which have been subject to metamorphic action. Very large individuals of muscovite also are met with in the pegmatitic veins (giant granite) associated with so many granitic masses.

THE OLIVINE GROUP

The minerals of this group are non-aluminous silicates. The only one of importance as a rock-former is **Olivine** (*Peridote*)—a silicate of magnesium and iron which crystallises in orthorhombic forms and shows an imperfect cleavage. It has a hardness of 6·5 to 7, and a specific gravity of 3 to 4. The proportion of iron varies—specimens containing very little being infusible, while those which are rich in iron are more or less readily fused. The mineral is slowly decomposed by cold hydrochloric acid with gelatinisation. It is usually yellowish-green or olive-green, has a glassy lustre, and breaks with a conchoidal fracture. As a rock-former it sometimes constitutes the whole mass or the larger proportion of a rock, as in dunites (peridotites). It is present also in many other igneous rocks—more especially in those of basic and intermediate composition, as certain gabbros, basalts, and felspathoid rocks. It is readily recognised in such rocks by the naked eye as granules or blebs, usually of a greenish tint with a glassy lustre, and showing its conchoidal fracture. Now and again it occurs in basalts as large granular aggregates resembling nodules, some of which may measure 5 or 6 inches across, but they are generally smaller. *Forsterite*, a light-coloured variety, is met with as a "contact mineral" in metamorphosed limestones. In nature, olivine alters readily to serpentine; probably, indeed, most serpentines have originated from the alteration of olivine-rocks. The finely coloured (yellow or green) transparent varieties of olivine are used in jewellery, and are known as *Chrysolite* and *Peridote.*

In thin rock-slices olivine is usually almost colourless, but may show pale yellowish-green or yellowish-brown tints. In basic eruptive rocks it appears sometimes in good crystal forms, with lozenge-shaped or long rectangular outlines (see Plate V. 1, 2), but the outlines are frequently rounded as if from magmatic corrosion. It shows high relief, the outlines of the mineral and the cracks traversing it being strongly pronounced. It is not pleochroic, but polarises rather brilliantly.

The Chlorite Group

Under this head are included certain greenish coloured minerals which are composed essentially of hydrated silicate of magnesium and aluminium, usually with some iron. As a rock-former **Chlorite** occurs in the form of pseudo-hexagonal non-elastic plates, but most frequently as bent and irregularly bounded scales, tufts, and fibres, or as scaly or earthy aggregates. Often it somewhat resembles mica. The hardness is 2 to 3, and the specific gravity 2·6 to 2·8. The only rock largely composed of this mineral is chlorite-schist. It occurs frequently, however, in eruptive rocks as a secondary product, from the alteration of such minerals as hornblende, augite, biotite, etc. Many igneous rocks, indeed, owe their greenish colour to the alteration of their original ferromagnesian constituents into chlorite. [Here also may be included *Glauconite*—a hydrous silicate of aluminium, potassium, and iron—which occurs in the form of small rounded granules of a greenish colour in certain sandstones of Cretaceous and Tertiary age; it is also met with in amygdaloidal cavities in igneous rocks.]

THE TALC AND SERPENTINE GROUP

Talc (hydrous silicate of magnesium) is a white or pale greenish mineral, readily cleavable into non-elastic folia, and so soft that it can be scratched with the finger-nail. Hardness = 1, specific gravity = 2·7 to 2·8. It has a pearly lustre and a pronounced greasy feel; is fusible on thin edges to a white enamel, but is not decomposed by acids. It never assumes a crystalline form. In igneous rocks it occurs rarely, and always as a secondary product, usually in the form of foliated plates and scales, replacing non-aluminous magnesian silicates. It is met with chiefly in the crystalline schists, being the chief ingredient of talc-schist.

Steatite (soap-stone) is a cryptocrystalline to compact variety of talc. *Potstone* is another but very impure variety. *Sepiolite* or *Meerschaum* is a closely allied mineral of essentially the same chemical composition. It is amorphous, occurring in irregular shaped nodules and masses, which are compact and finely porous. When dry it floats in water, which it absorbs greedily. Like talc, it is eminently a product of the alteration of magnesian silicates. As a rock-former it is of no importance.

Serpentine (hydrous silicate of magnesium, often containing iron; hardness = 3 to 4; specific gravity = 2·5 to 2·7), like talc, never assumes a crystalline form, but occurs in compact or granular masses and in aggregates with a lamellar, scaly, or fibrous structure. The colour is some dark shade of green, red, or yellow, often mottled or variegated. The finely fibrous variety is known as *Chrysotile* (see Plate VI.). [Most of the "asbestos" of commerce is not true asbestos, but chrysotile.] Serpentine is fusible with difficulty on thin edges, and is decomposed by hydrochloric acid. It is always a secondary mineral—a product of the alteration of ferromagnesian minerals, as olivine, pyroxenes, amphiboles, etc.

It is the chief constituent of the rock serpentine. *Noble Serpentine* is a pure variety of a uniform colour (green or yellow), which takes on a fine polish, and is used as an ornamental stone.

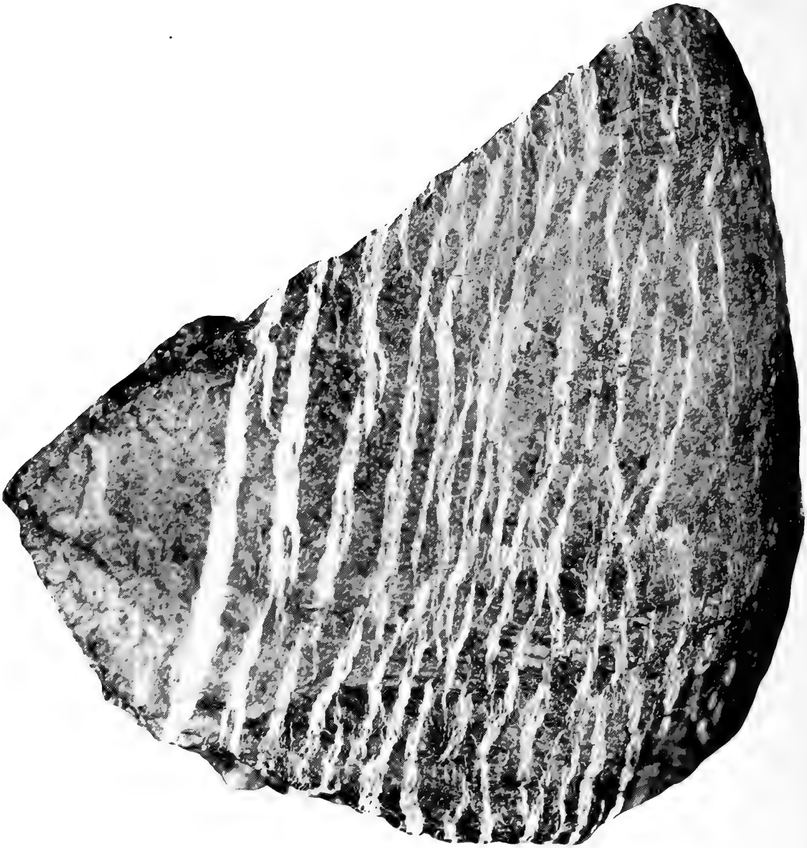
THE EPIDOTE GROUP

The principal rock-forming member of this group is **Pistazite**, or iron-epidote—so called to distinguish it from *Zoisite*, or lime-epidote. Pistazite is a silicate of calcium, aluminium, and iron, which occurs crystallised in monoclinic forms, or appears in finely granular masses of a peculiar pistachio-green colour. The hardness is from 6 to 7, and the specific gravity 3·2 to 3·5. The mineral fuses with difficulty before the blowpipe, and is partially decomposed by hydrochloric acid. It is met with frequently as a constituent of schistose rocks (epidote-gneiss, epidote-amphibolite), and as a "contact mineral" in limestones, etc., which have been affected by the intrusion of igneous rock. It is a common alteration-product in eruptive rocks, replacing such minerals as hornblende, biotite, felspars, etc., and often associated with chlorite. **Zoisite** (orthorhombic) is a silicate of calcium and aluminium, met with not infrequently in schistose rocks and as an alteration-product of felspar in gabbro. [*Clinozoisite* is a monoclinic epidote containing little iron, and approaching to zoisite in composition.]

THE GARNET GROUP

Garnets are silicates of aluminium, iron, calcium, magnesium, chromium, and manganese, usually only two or three of these being abundantly present. According to the dominance of the chief constituents, we have iron-, calcium-, magnesium-, manganese-aluminium garnets, etc. They usually assume dodecahedral (see Plate I. 3) or icositetrahedral forms, and have an imperfect cleavage. The hardness is 6·5 to 7·5, and the specific gravity 3·4 to 4·3. The lustre is greasy or resinous. Common rock-forming iron-aluminium garnet is generally some shade of red—hyacinth to reddish-brown. It is fusible before the blowpipe, but is not readily decomposed by acids. In nature it alters chiefly to chlorite, and sometimes to serpentine, epidote, etc. Under the microscope its sections are rounded or many-sided ; it shows no cleavage, but irregular cracks which are not infrequently lined with decomposition-products. Enclosures often abound. Usually garnet remains dark when rotated between crossed nicols. It is common in many schists, is an essential constituent of eclogite and garnet-rocks, and occasionally occurs in granite and quartz-porphyry. Calcium-aluminium garnet is often present as a "contact mineral" in metamorphosed limestone. The clear, finely coloured varieties of garnet have some value as gems ; amongst these are *Almandine* (iron-aluminium garnet) and *Pyrope* (magnesium-aluminium garnet), the former occurring in schists and granite, the latter in peridotites and serpentine. *Melanite*, a black calcium-iron garnet, is met with in some trachytes, phonolites, and other volcanic rocks.

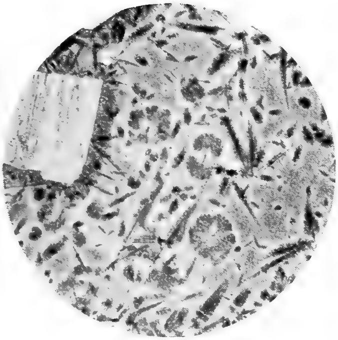
PLATE VI.



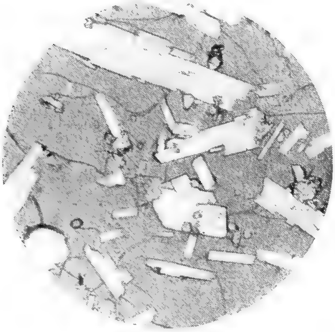
SERPENTINE VEINED WITH CHRYSOTILE. Natural size.

PLATE VII.

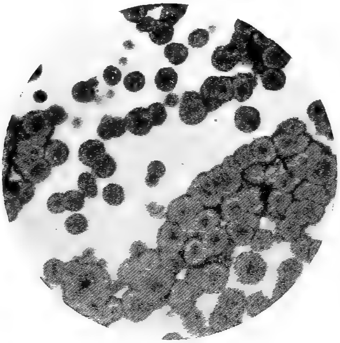
MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS.



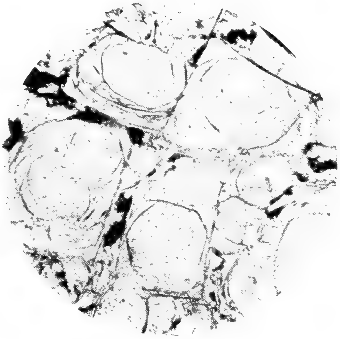
1.



2.



3.



4.

1. Crystallites and Microlites in glassy base. Pitchstone.
2. Lath-shaped crystals of Felspar in glassy base. Andesite.
3. Spherulites in clear glass. Obsidian.
4. Perlitic structure. Pitchstone.

[*Between pages 24 and 25.*

Cordierite (*Dichroite*, *Iolite*) is a magnesium-aluminium silicate, containing a little iron. It crystallises in orthorhombic forms. Hardness = 7 to 7·5; specific gravity = 2·59 to 2·66. It is usually some shade of blue, has a vitreous lustre, is hardly attacked by acids, and fuses with difficulty before the blowpipe. It occurs in many schistose rocks, especially in gneisses, in eruptive rocks (granites, quartz-porphyries, rhyolites, andesites), and as a product of contact-metamorphism, in the form of granular aggregates, in the rocks known as "hornfels."

The Tourmaline Group

Tourmaline crystallises in rhombohedral (hemimorphic) forms. It has a complicated and variable chemical composition, but is essentially a borosilicate of aluminium, with magnesium, iron, alkalies, fluorine, and basic water. Its hardness is 7 to 7·5, and specific gravity 2·94 to 3·24. It is not attacked by acids, but is fusible, the degree of fusibility varying with the chemical composition. The only form of any importance as a rock-constituent is the black variety, **Schorl**, which often occurs as long trigonal prisms longitudinally striated; appears also as microscopic prisms and grains, or as groups of acicular crystals with a radiated arrangement; occasionally it is met with as massive aggregates. It varies from very dark green to black. The cleavage is indistinct, and this, with its greater hardness and the form of the prisms, serves to distinguish schorl from hornblende, which it often resembles in colour and pleochroism. It is often a constituent of schistose rocks, and not infrequently an ingredient of acid plutonic rocks, especially granite. It occurs commonly as a "contact mineral" in the zone of altered rocks surrounding granite, etc. The mineral does not weather readily. The transparent, beautifully coloured tourmalines are in some request for jewellery.

The Titanite Group

Titanite or **Sphene** is really the only member of this group, the others being merely varieties of the same mineral. As a rock-former titanite is a widely distributed accessory ingredient of eruptive rocks (especially of hornblendic granite, syenite, diorite, etc.), and occurs also in certain schistose rocks and crystalline limestones. It is a silicate and titanate of calcium, crystallising in monoclinic forms, which are usually lozenge- or wedge-shaped (see Plate IV. 3). It is decomposed by sulphuric and hydrofluoric acids, and fuses with difficulty. Its hardness is 5 to 5·5, and its specific gravity 3·4 to 3·6. Its colour is yellowish to brown. Well-formed crystals often appear in the drusy cavities of granite, in gneiss, and in metamorphosed limestones. As an accessory ingredient of eruptive rocks it is usually of microscopic size. *Leucoxene* is a dull white or grey earthy form of titanite, which occurs as an alteration-product of ilmenite. Sphene is a somewhat stable mineral, being not readily weathered.

The Andalusite Group

These are silicates of aluminium, crystallising in orthorhombic and triclinic forms, and occurring chiefly in crystalline schists and in rocks which have been affected by the action of intrusive masses. The members of the group of most frequent occurrence as rock-formers are *Andalusite* (with its variety *Chiastolite*), *Sillimanite*, *Kyanite*, and *Staurolite*. The first three are silicates of aluminium alone, while staurolite contains iron and magnesium in addition.

Andalusite occurs not infrequently as well-developed columnar prisms (orthorhombic) in mica-schist and gneiss, and is often a notable ingredient of the altered rocks surrounding a mass of granite. Hardness 7 to 7·5 ; specific gravity 2·94 to 3·2. It is usually more or less crowded with inclusions ; and when these are regularly arranged so as in cross-sections of the prism to show a cruciform or tesselated pattern, we have the variety known as *Chiastolite* (see Plate V. 3, 4). This variety is of common occurrence in argillaceous rocks, which have been affected by intrusions of granite. **Sillimanite** assumes the form of thin rod-like or needle-like orthorhombic prisms, occurring sometimes under the same conditions as chiastolite, but met with chiefly in crystalline schists. The finely fibrous aggregates appearing in the form of lenticular lumps are known as *Fibrolite*. **Kyanite** is a white or pale blue mineral, crystallising in long broad flattened prisms (triclinic), and occurring in certain crystalline schists, but never in igneous rocks. A remarkable character of kyanite is its hardness, which is not the same in different directions ; along the broad lateral planes it is only 5, while across these it is 7. It is often associated with garnet and **Staurolite**—the latter being a dark brownish-red mineral which assumes the form of short and thick or long and broad columnar crystals (orthorhombic). Interpenetrating cruciform twins of staurolite are very common. It does not occur in eruptive rocks. This mineral is not readily weathered.

THE ZEOLITE GROUP

The **Zeolites** are essentially decomposition-products, and frequently occur in igneous rocks as the result of the alteration of certain original constituents. They are all hydrated silicates of alumina and alkalies with, in many cases, lime. As a rule they are colourless, and usually transparent to translucent. The water they contain is readily driven off before the blowpipe, and most of them are easily decomposed by acids. They occur chiefly in the vesicular cavities and fissures of eruptive rocks, or they may replace some of the original constituents of these rocks, more especially the felspars and felspathoids. Among the more commonly occurring species are *Analcite*, *Stilbite*, *Natrolite*, *Chabazite*.

THE KAOLINITE GROUP

Various decomposition-products may be included in this group, of which much the most important is the hydrated silicate of alumina—**Kaolinite**. When pure this mineral is usually white, earthy, or mealy. Occasionally, under the microscope, this white powder may be seen to consist largely or entirely of minute transparent or translucent plates, with pseudo-hexagonal symmetry. Before the blowpipe it is infusible, and is insoluble in acids; hardness = 1; specific gravity = 2·5. It is a common alteration-product of many rock-forming aluminous silicates, notably orthoclase, albite, and lime-soda felspars. When moistened with water, it is highly plastic. Impurities are usually present, particularly iron-oxides, which give it a yellow, red, or brown colour; other colours met with are grey, blue, and green. *Lithomarge* is merely an impure compact kaolin; it is often mottled red owing to the presence of ferric hydrate.

III. HALOIDS

Fluor-spar or **Fluorite** (calcium fluoride) is hardly entitled to be called a rock-former. It occurs rarely as rounded grains in granitic, syenitic, and gneissic rocks, where it is apparently of secondary origin. It is met with, however, frequently as a gangue-mineral in lodes, particularly in association with lead- and tin-ores. The common form of the crystallised mineral is a cube, and interpenetrating twins often occur. The colour is variable—violet, blue, green, yellow, and occasionally pink. Thick veins of granular fluor-spar appear now and again, traversing crystalline schistose rocks, especially in the neighbourhood of granite masses. The mineral has a hardness of 4 and a specific gravity of 3·2. It is decomposed by sulphuric acid, but hardly attacked by other acids, and fuses with some difficulty before the blowpipe.

Rock-salt (sodium chloride) crystallises in the form of cubes, but occurs massive as a rock in beds, associated with anhydrite and gypsum. It is met with also as a product of sublimation in volcanic regions, along with calcium- and magnesium-chlorides and calcium-sulphate.

IV. SULPHIDES

Pyrite (disulphide of iron) commonly crystallises in cubes and octahedra, but not infrequently occurs as irregular aggregates. It has a very uniform, brass-yellow colour. Hardness = 6 to 6·5; specific gravity = 4·9 to 5·2; streak = black. Before the blowpipe pyrite gives off sulphur, burning with a blue flame. It is decomposed by nitric acid. The only minerals with which pyrite might possibly be confounded are chalcopyrite (an ore of copper), magnetic pyrite, and perhaps gold. Gold, however, is malleable, and the others are not. Pyrite is paler and considerably harder (6 to 6·5) than chalcopyrite (3·5 to 4)—the streak of the former being black, while that of the latter is greenish-black. *Magnetic Pyrite* or *Pyrrhotite* (an iron-sulphide of variable composition) has a characteristic pinchbeck-bronze colour, is slightly magnetic, and not so hard as pyrite, while the streak is greyish-black. Pyrite often occurs in the form of detached crystals and aggregates in clay-slate. It is an occasional ingredient of schistose rocks, sandstone, coals, and argillaceous rocks of various kinds, often as fine-grained impregnations. Now and again it appears as an accessory mineral in eruptive rocks. It is of frequent occurrence also in lodes, either as crystal aggregates or massive. Pyrrhotite is not so common a rock-former as pyrite. Occasionally it is present in basic igneous rocks (gabbro, basalt, etc.) and schists (amphibole rocks). Like pyrite, it often occurs in metalliferous veins—the two minerals being not infrequently associated in the so-called "bedded veins" or "quasi-bedded ore formations."

Marcasite is an orthorhombic mineral, having the same composition as pyrite. It occurs usually compact or cryptocrystalline, and is often disseminated in minute grains through certain sedimentary rocks. Radiated nodular forms are also very common. The hardness is the same as that of pyrite, and the specific gravity slightly less. It is a less stable form than pyrite. The colour is bronze-yellow, inclined often to green or grey. It has hardly so wide a distribution as pyrite, occurring chiefly as concretions in argillaceous and calcareous rocks.

V. CARBONATES

Calcite or **Calc-spar** (calcium carbonate) crystallises in the hexagonal system, and assumes a great variety of crystalline forms. The cleavage is rhombohedral, as exemplified by the well-known transparent Iceland spar, so commonly used for polarising instruments; but the unit rhombohedron is a rare crystal. Scalenohedral forms are very common, as in dog-tooth spar. Calcite is recognised by its slight hardness (= 3), as it is easily scratched with the penknife, by the readiness with which it effervesces briskly with dilute hydrochloric acid, and by its marked rhombohedral cleavage. The specific gravity is 2·6 to 2·8. Calcite is an important constituent of many aqueous deposits—as limestone, marble (Plate IX. 2), calc-sinter, etc. It is a frequent binding material in sedimentary rocks. As a secondary product, it appears commonly in the minute pores and capillaries of many different minerals and rocks; it also occupies cracks, fissures (see Plate XV.), and cavities of all kinds—being a common gangue-mineral in lodes. It is the chief petrifying agent, and, next to quartz, the commonest of all minerals.

Aragonite has the same composition as calcite, but crystallises in the orthorhombic system. Its hardness (3·5 to 4) and specific gravity (2·9 to 3) are both somewhat greater than those of calcite. It is a more soluble form of calcium-carbonate than calcite, and not nearly so common as that mineral. Sometimes it is met with in beds associated with gypsum and iron-ore, and not infrequently in cracks and cavities in recent eruptive rocks. It is often a deposition from hot-springs.

Dolomite or **Bitter Spar** (calcium and magnesium carbonate) crystallises in the hexagonal system—the faces of the crystals being frequently curved. Hardness = 3·5 to 4·5; specific gravity = 2·85 to 2·95. It is only slightly affected by cold dilute hydrochloric acid, but is dissolved when the acid is heated. It may be variously coloured, but white and yellow varieties are most common. Magnesian limestone is composed in large part of this mineral.

Siderite or **Chalybite** (carbonate of iron) occurs usually in rhombohedral forms, often with curved faces. It is colourless or pale yellow when freshly exposed, but soon becomes tarnished brown or rusty. Hardness = 3·5 to 4·5; specific gravity = 3·7 to 3·9; the mineral is infusible before the blowpipe, but effervesces with weak acids. It occurs in lodes along with various ores. *Sphærosiderite* is the name given to a compact siderite often showing a concentric, radiating, fibrous structure. It occurs as nodules and nodular masses in veins and cavities in crystalline schists, etc. *Clay-ironstone* is an impure variety of sphærosiderite mixed with clay, which occurs as nodules, bands, and beds in various geological formations. *Blackband-ironstone* is a clay-ironstone containing a notable amount of carbonaceous matter. [Clay-ironstone and blackband-ironstone are rather rocks than minerals.]

VI. SULPHATES

Anhydrite (calcium sulphate) crystallises in the orthorhombic system, but usually occurs massive or in granular and fibrous aggregates. It is often associated with rock-salt and gypsum. Hardness = 3 to 3·5; specific gravity = 2·9 to 3. It is slightly soluble in hydrochloric acid, and fuses before the blowpipe with difficulty to a white enamel, colouring the flame reddish-yellow.

Gypsum (hydrated calcium sulphate) crystallises in monoclinic forms, its hardness (1·5 to 2) and specific gravity

(2·2 to 2·4) being considerably less than those of anhydrite. It may be variously coloured, but is usually transparent or white. It is soluble in hydrochloric acid. Before the blowpipe it becomes opaque or white, exfoliates, and fuses to a white enamel. Crystals, lenticular concretions, and interrupted layers of gypsum often occur in clays. Frequently it appears as granular and compact masses, arranged as layers and thick beds in argillaceous strata, where it is commonly associated with rock-salt and anhydrite. Now and again it forms the cement or binding material of sandstone. *Selenite* is the name given to crystallised gypsum; it shows perfect cleavage—the laminæ being flexible but not elastic. The very fine-grained cryptocrystalline kinds are usually termed *Alabaster*, and the fibrous varieties *Satin Spar*.

Barytes or **Heavy Spar** (barium sulphate) crystallises in the orthorhombic system. Fibrous varieties are common. It is not, properly speaking, a rock-former, but is usually met with as a secondary mineral in veins and other cavities. It is commonly associated with ores (especially sulphides) in lodes. Its hardness (3 to 3·5) slightly exceeds that of calcite, but its greater specific gravity (4·3 to 4·6) and its resistance to acids at once distinguish it from the latter. Barytes decrepitates and fuses with great difficulty before the blowpipe, colouring the flame yellowish-green.

VII. PHOSPHATES

Apatite (phosphate of lime, containing either fluorine or chlorine: hence, chemically, two kinds are recognised—fluor-apatite and chlor-apatite). This mineral crystallises in the hexagonal system, usually as six-sided prisms. Hardness = 5; specific gravity = 3·17 to 3·23. It is soluble in hydrochloric acid, and fusible with difficulty before the blowpipe. It occurs as a frequent but usually a microscopic accessory ingredient of very many eruptive rocks and crystalline schists, commonly in the form of long, slender, hexagonal prisms or needles. It is a frequent inclusion in all the essential constituents of eruptive rocks. Next to magnetite, it has the widest distribution of all accessory rock-constituents. Fine crystals occur in the drusy cavities of some granites, as likewise in gneisses. It is met with also as irregular layers (often associated with magnetite) among schistose rocks; while crystals, large and small, not infrequently appear in talc- and chlorite-schists, and in metamorphosed limestones. Again, it forms independent veins of large size, associated with gabbro. The earthy and concretionary varieties of phosphate of lime are known as *Phosphorite*—and many of these are of organic origin.

VIII. ELEMENTS

Carbon, in the form of **Graphite,** is the only element which plays a relatively considerable part as a rock-former. Graphite is usually not crystallised, but sometimes it appears as flat, six-sided plates. Hardness =1; specific gravity=2. It is black, with an almost metallic lustre; has a greasy feel; and yields a black and shining streak. It is not affected by acids. It occurs as a constituent (sparingly or abundantly, as the case may be) of many schistose rocks and slates, as in graphite-schist, graphite-gneiss. Now and again lenticular beds of it appear among schists, and not infrequently it occupies veins and other cavities traversing such rocks. It has been met with also in granite and basalt. Coal is sometimes converted into graphite by contact with eruptive rock, as at New Cumnock and near Shotts, in Scotland.

Many minerals and rocks are rendered dark or even black owing to the quantity of carbonaceous matter they contain. When the carbonaceous matter is quite amorphous (*i.e.* destitute of crystalline form and structure) it is readily driven off by heating. (Pure graphite, however, burns only with the greatest difficulty before the blowpipe.) The amorphous carbonaceous colouring matter of black marble, etc., is apt to become oxidised on exposure to the weather, and changed into carbon-dioxide, so that the rock tends to bleach and whiten.

CHAPTER III

ROCKS

Classification:—Crystalline Igneous Rocks—their general characters. Chief Minerals of Igneous Rocks. Primary and Secondary Minerals. Law of Mineral Combination. Groups of Igneous Rocks:—Rocks with Dominant Alkali Felspar; Rocks with Dominant Soda-Lime Felspar; Rocks with Felspathoids in place of Felspars; Rocks without Felspars or Felspathoids; Pyroclastic Rocks.

THE term "rock," as used by the geologist, means any mass or aggregate of one or more kinds of mineral or of organic matter, whether hard and consolidated or soft and incoherent, which owes its origin to the operation of natural causes. Thus granite, basalt, limestone, clay, sand, silt, and peat, are all equally termed rocks.

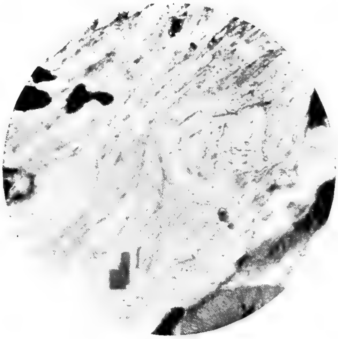
Speaking generally, we may say that the unconsolidated rocks occupy for the most part a superficial position—overspreading and concealing the consolidated rocks of which the earth's crust is chiefly composed. There are many exceptions to this rule, however. Sometimes, for example, unconsolidated materials occur at considerable depths from the surface, buried under masses of hard rock. Nor is the relative age of a rock always indicated by the degree of its consolidation. Many incoherent rocks are of great geological antiquity; while, on the other hand, some rocks of quite recent age are nevertheless as hard and resistant as the oldest.

Classification of Rocks.—The rocks of which the earth's crust is constructed are very diverse in character and origin. Some owe their origin to eruptive and volcanic forces; others are obviously composed of materials which have been derived from the disintegration of pre-existing rock-masses; while yet others have undergone certain more or less fundamental

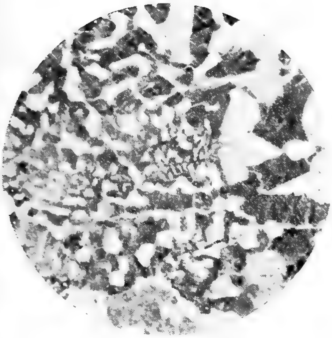
PLATE VIII.

MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS.

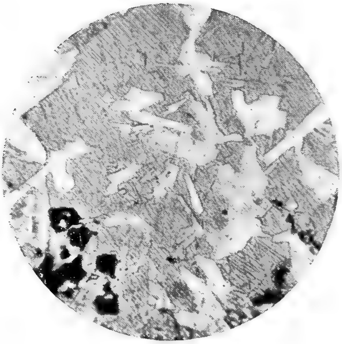
1.



2.



3.



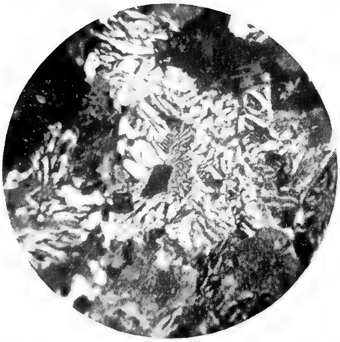
4.

1. Banded Obsidian.
2. Fluxion structure in Pitchstone.
3. Pegmatitic structure: intergrowth of Quartz and Felspar. Graphic Granite.
4. Ophitic structure: lath-shaped crystals of Felspar enclosed in a large plate of Augite, which shows parallel cleavage. Diabase.

[*To face page* 32.

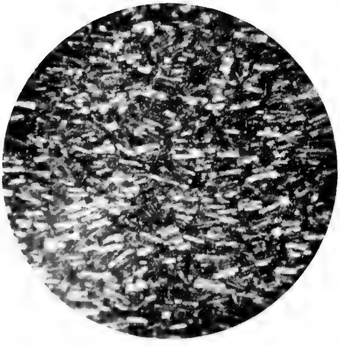
PLATE IX.

MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS.

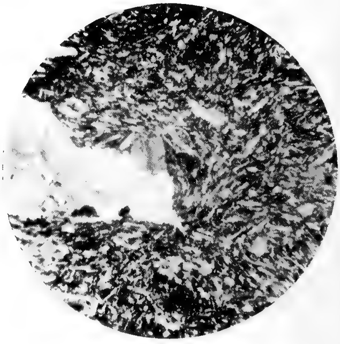


1.

2.



3.



4.

1. Granophyric structure: minute intergrowth of Quartz and Felspar. Granophyre. Nicols crossed.
2. Calcite, with rhombohedral twinning and cleavage. Marble. Nicols crossed.
3. Trachytic structure: small crystals of Felspar in fluxional arrangement. Bostonite. Nicols crossed.
4. Trachytic structure: microlites of Felspar eddying round a group of larger crystals of Sanidine. Trachyte. Nicols crossed.

[*To face page* **33.**

changes since the time of their formation, so that it is not always possible to tell what their original character may have been. We have thus three more or less well-marked types of rocks, which may be termed **Igneous, Derivative,** and **Metamorphic** rocks respectively.

I. IGNEOUS ROCKS

This division includes all masses which owe their origin to the operation of eruptive and volcanic forces. Some of these rocks consist either wholly or in part of crystalline ingredients, while others are composed of fragmental materials. Hence we have two groups, viz.:—A. **Crystalline,** and B. **Fragmental** or **Clastic Igneous Rocks.**

A. Crystalline Igneous Rocks

The rocks of this group vary much in character. Some are thoroughly crystalline, while others consist partly of crystalline minerals and partly of non-differentiated matter—the relative proportion of crystalline and non-crystalline ingredients varying indefinitely.

All these rocks have consolidated from a state of igneous fusion—the general character of each having been largely determined by the conditions under which the original molten matter or magma has cooled and solidified. That magma has a complex chemical composition, but may be said to consist essentially of a mixture of several silicates and oxides, with water and various gases. As soon as the temperature of this mixture begins to fall, the commingled ingredients commence to separate out successively—in other words, molecules of a like kind gather and group themselves together to form crystals. Sometimes the cooling process is so protracted that all the several compounds constituting the magma have time to become thoroughly crystallised. In other cases solidification takes place more rapidly, so that crystallisation is only partially effected, and the resulting rock then consists of a mixture of crystalline ingredients and glassy or non-differentiated matter. Occasionally, indeed, cooling and consolidation proceed so promptly that no crystals have time to form before the whole mass congeals to form a vitreous rock, throughout which the several mineral compounds exist in essentially the same diffused condition as in the molten magma. It will be understood, then, that when a molten mass cools and consolidates rapidly, a *glassy* or *vitreous* rock results; with less rapid cooling a *hemicrystalline* rock is formed; while very slow cooling gives rise to a *holocrystalline* rock. But as traces of crystallisation are rarely or never quite absent from a volcanic glass, all these types may, for purposes of description, be included under the head of crystalline igneous rocks.

Vitreous Rocks. *Their General Character.*—Many of these seem to the unassisted eye smoothly homogeneous, and to contain no trace of crystalline ingredients. When thin slices, however, are subjected to microscopic examination, they rarely fail to show, in less or greater abundance, certain minute bodies, some of which have obviously a crystalline structure, while others show no such structure, but may be looked upon as merely the embryos of crystals. Some of these forms are shown in Plate VII. 1. *Crystallite* is the name given to the minute bodies which do not react on polarised light, and are apparently destitute of crystalline structure. As a rule crystallites afford no hint as to the nature of the mineral into which they might have developed had their growth not been arrested. Other minute bodies (*Microlites*) which give a definite reaction with polarised light, show a further stage in crystal-development, and are often of such a character that it is possible to say to what mineral species they belong. Besides crystallites and microlites, more or less well-developed crystals of relatively large size may occur disseminated through a vitreous rock (see Plate VII. 2).

Certain other structures of frequent occurrence in glassy rocks may be briefly referred to. Amongst these are small globules termed *Spherulites* (see Plates VII. 3; XIII. 1). They vary in size from a millet-seed to a pea, and under the microscope show an internal divergent or radiating fibrous structure. Similar spherical bodies, sometimes larger than hazelnuts, are now and then developed in artificial glass, their internal fibrous structure being quite apparent to the naked eye. Not infrequently, glassy rocks contain small enamel-like globules, which, in thin sections under the microscope, often exhibit an imperfectly developed concentric or *perlitic* structure (see Plate VII. 4). Spherulites may occur sporadically or be closely packed together; and, similarly, perlitic structure may be sparsely or abundantly developed—some glassy rocks, indeed, appearing as if composed entirely of enamel-like globules. A vitreous rock having this character well marked is often termed *Perlite.*

There are certain other structures which, although not confined to vitreous rocks, are nevertheless more or less characteristic of these.

Frequently, the crystallites, microlites, crystals, and spherulites contained in a glass appear arranged in lines or in bands; very often, too, the glass shows a ribboned or striped appearance—darker and lighter coloured layers rudely alternating (see Plates VIII. 1, 2; XIII. 2). This is known as *Fluxion* or *Fluidal* structure, and is obviously due to the differential movement of the rock while it was still in a mobile condition.

All molten masses contain water and various *vapours* and *gases*, which are given off in dense clouds from a lava at the time of its eruption. When the lava is very liquid the steam readily escapes; but as the mass on cooling becomes more viscous the vapours are less easily got rid of. They segregate and expand, pushing the plastic rock aside and thus forming spherical cavities. In this way the upper portion of a lava is often rendered more or less vesicular. As the lava flows on its way the spherical cavities become flattened and drawn out in the direction of movement. The vesicles vary in size from mere pores up to cavities, measuring more than one foot across; but cavities of such a size occur only sporadically. In the case of vitreous rocks which have flowed out in a highly liquid condition, the vesicles are rarely large. Usually they are so small and so very abundant that they may occupy fully as much space as the solid portion which contains them. Vitreous rock of this kind has a spongy, froth-like appearance, and is known as *Pumice*. The vesicles formed in very viscous lavas are usually larger and not so abundant.

Hemicrystalline Rocks. *Their General Character.*—These rocks are composed chiefly of crystalline ingredients, with a larger or smaller proportion of non-differentiated matter. Typically, a hemicrystalline rock contains the following constituents:—(*a*) *Groundmass*, an aggregate of microlites and small crystals or crystalline granules, with which some amount of glass (not infrequently devitrified) may or may not be associated; (*b*) *Phenocrysts*, the term applied to the larger crystals disseminated through the groundmass.

Most hemicrystalline rocks have consolidated at or near the surface of the earth. While they were still in a molten condition, however, and at some considerable depth in the crust, cooling had already commenced, and certain minerals had crystallised out. Such minerals, therefore, being free to develop, often attained a relatively large size and a more or less perfect crystalline form. Not infrequently, however, they show corroded outlines, as if they had been partially dissolved. This is supposed to have been caused by the action of the still fluid portion of the magma—rendered more acid as it would be after the phenocrysts had separated out. Probably the process of resorption was aided also by changes of pressure and temperature as the molten rock rose towards the surface. Not only are the phenocrysts frequently corroded, but they have often been broken during movements of the magma. Thus, when a molten mass eventually reached the surface, it already contained many disseminated solid particles—the *phenocrysts*. No sooner did the lava begin to flow than cooling proceeded so rapidly that large and approximately perfect crystals could no longer be formed—the numerous mineral bodies interfering with each other's growth and thus forming a close aggregate, diffused through which glassy matter might occur either sparingly or abundantly. This is the so-called groundmass. When phenocrysts are conspicuously present in it we have what is known as *porphyritic* structure (see Plates X.; XII. 1). It will be understood, therefore, that such porphyritic rocks give evidence of two stages of consolidation—the phenocrysts belonging to the earlier or *intratelluric*, and the groundmass to the final or *volcanic* stage.

The groundmass of hemicrystalline rocks is as a rule mostly made up of crystalline ingredients. In some of these rocks, however, it consists chiefly of glass, while in many others crystalline constituents and glass are approximately equal in amount. The non-differentiated matter or *base* of the groundmass not infrequently assumes a *microfelsitic* or *cryptocrystalline* character. To the unassisted eye this substance seems to be quite compact and homogeneous; but under the microscope microfelsitic matter appears as an indefinite aggregate, or nearly structureless mass.

As might have been expected, the non-differentiated matter in the groundmass frequently shows the structures which have already been described as characteristic of volcanic glass. It is often more or less devitrified and stony-like, owing to the abundant development of crystallites and microlites, while spherulitic and perlitic structures are of common occurrence. Fluxion structure also is often seen, not only in the base but throughout the whole groundmass. Lastly, vesicular structure, as already indicated, is just as characteristic of hemicrystalline as of vitreous rocks.

Holocrystalline Rocks. *Their General Character.*—These rocks contain no non-differentiated matter—they have no base, and as a rule no proper groundmass (see Plate XII. 2). Not infrequently, however, they show conspicuous phenocrysts disseminated through the relatively fine-grained crystalline aggregate which constitutes the mass of the rock. Such rocks would therefore seem to have experienced two stages of solidification—the phenocrysts, as usual, having crystallised out first. Both stages of solidification, however, were intratelluric — holocrystalline rocks being usually of more or less deep-seated origin. They differ greatly in texture, some being very finely crystalline, while others are exceedingly coarse-grained, and between these extremes all intermediate textures occur.

Mineral Ingredients of Igneous Rocks.—Many different minerals enter into the composition of igneous rocks, anhydrous silicates being by far the most important. Save in the case of well-developed phenocrysts and the smaller accessory ingredients, these minerals are not as a rule completely bounded by crystal faces. When they are thus bounded they are said to be *euhedral* or *idiomorphic.* Should only some of the crystal faces appear (and this is very often the case with those minerals which were the first to crystallise out after the phenocrysts and smaller accessories had appeared), then the structure is termed *subhedral* or *hypidiomorphic.* Most commonly, however, the minerals, owing to mutual interference, have not assumed the geometrical forms which would have distinguished them had they crystallised under more favourable conditions. Minerals thus devoid of their proper crystalline form are described as *anhedral* or *allotriomorphic*—their shape has been determined by their surroundings.

Inclusions in Minerals.—When examined in thin slices under the microscope, the minerals of igneous rocks are often seen to include minute crystals or crystalline granules of other minerals. Not infrequently, also, cavities, containing gas or liquid, or, it may be, glass or stony matter, appear in less or greater abundance (see Plates I. 2 ; IV. 4 ; VIII. 4). These inclusions are termed *endomorphs*—the minerals which contain them being termed *perimorphs*. Obviously, all these foreign bodies must have been caught up and enclosed while the perimorphs were separating out from the original molten magma.

Primary or Original Minerals.—Those rock-constituents which crystallised out from the magma are termed *primary* or *original*, to distinguish them from another group of minerals which are of later origin than the rocks in which they occur. Two kinds of primary minerals are recognised—namely, (*a*) **Essential** and (*b*) **Accessory** minerals. Essential minerals are those which determine the species of a rock, while accessory minerals are, as it were, mere accidental ingredients, the presence or absence of which does not affect the general character of a rock. Granite, for example, is composed of three essential minerals—felspar, quartz, and mica. Take away any one of those, and the rock ceases to be a granite. One or more non-essential ingredients, however, may be present, and yet the rock remains a granite. Should one of these accessory minerals be very abundant or conspicuous, it may give rise to a variety. If a granite, for example, contains conspicuous crystals of hornblende or of tourmaline, it is termed a hornblendic or a tourmaline granite, as the case may be.

Secondary Minerals.—All rocks are subject to alteration, due especially to the action of water percolating through them. This water finds its way along fissures and other planes of division, and soaks into the rock itself through the minute cracks, capillaries, and interstitial pores, which are never wanting in even the most compact and homogeneous kinds. The percolating water contains carbon-dioxide or other acid in solution, which has been taken up from the atmosphere by rain, or absorbed from the soil. Thus armed, the water attacks the various mineral constituents of rocks, which in this way may be more or less profoundly altered. Some yield much more readily than others, but sooner or later the several silicate minerals, of which igneous rocks are so largely composed, tend to be chemically broken up—such bases as the alkalies and alkaline earths being removed in solution as bicarbonates. Some crystalline igneous rocks have been so much affected by the chemical action of water, that they have been changed from hard, resisting masses, showing a sparkling lustre on freshly fractured surfaces, to dull, soft, earthy, or clay-like substances, which may be dug with a spade. Few igneous rocks, indeed, which have been long exposed to the insidious action of percolating water, fail to show some trace of alteration. They may appear to be fresh to the unassisted eye, but thin slices viewed under the microscope will almost invariably show that one or other of their mineral constituents has undergone change. The felspar of a granite, for example, is a mineral which, when unaltered, appears quite clear and transparent in thin slices. When alteration has commenced, this is shown by a clouded or turbid aspect, affecting the whole or a portion only of the mineral. Increasing turbidness marks increasing chemical alteration; until eventually all trace of the original felspar disappears, and its place is occupied by a white or greyish homogeneous substance. This substance is the hydrous silicate of alumina, known as *kaolinite*, and is obviously the result of the complete decomposition of the felspar which it replaces. As felspar is an anhydrous silicate of alumina and alkali or alkaline earth, the chief change brought about has been the removal of the soluble bases—the more resisting silicate of alumina being left behind as a hydrate. It is quite common, in this way, for certain minerals of igneous rocks to become changed into other mineral species, either by the gain or loss of some ingredient, or by the gain of one ingredient and the loss of another. The new mineral thus formed is known as an *alteration-pseudomorph*;* and all such products of alteration are termed *secondary* minerals—they are thus of later origin than the rock of which they form a portion.

It will be understood now that secondary minerals are simply the products of the chemical alteration of essential and accessory minerals. They not only replace in whole or in part these primary or original constituents, but are frequently met with lining or filling cracks and fissures, or occupying the vesicular cavities of igneous rocks.

Chief Minerals of Igneous Rocks.—A large number of minerals enter into the composition of igneous rocks—the more important of which have been described in preceding chapters. These, as we have seen, naturally fall into two groups: (1) PRIMARY or ORIGINAL, and (2) SECONDARY minerals. The former group includes two kinds, namely, *Essential* and *Accessory*, and may be tabulated as follows:—

PRIMARY OR ORIGINAL MINERALS

In list I. we include the most important, namely, those which have the widest distribution and occur most abundantly—those, in short, which are the chief ingredients of the commonest igneous rocks. The minerals given in italics are of less importance than the others. All the

---

* A pseudomorph is simply a crystalline or amorphous body which has assumed the crystalline form of another mineral. There are several kinds of pseudomorphs. In certain cases a mineral may be dissolved out of a rock and a cavity or mould left; subsequently mineral matter of a different kind may be introduced by infiltration into the cavity, in which case we have a *substitution-pseudomorph*.

minerals in the list are essential constituents in some rocks, and accessory ingredients in others :—

I.

1. Quartz.
2. Felspars.
3. Pyroxenes.
4. Amphiboles.
5. Biotite.
6. Olivine.
7. *Nepheline.*
8. *Leucite.*

The minerals named in list II. are of less importance—the igneous rocks of which they are essential constituents being of more local occurrence. As accessory ingredients, however, they play a notable part, some of them (muscovite, garnet, schorl, sphene) having a very wide range indeed :—

II.

1. Muscovite.
2. Sodalite.
3. Haüyne and Nosean.
4. Garnet.
5. Schorl.
6. Sphene.

The minerals in list III. occur chiefly as accessory ingredients, and are thus of subordinate importance to those already mentioned, but they are all very widely distributed :—

III.

1. Apatite.
2. Magnetite.
3. Ilmenite.
4. Hæmatite.
5. Pyrite.
6. Zircon.
7. Rutile.

List IV. includes accessory ingredients which are not so widely distributed as those already mentioned :—

IV.

1. Spinel.
2. Chromite.
3. Picotite.
4. Pyrrhotite.

SECONDARY MINERALS

There are many minerals of secondary origin, but only the more commonly occurring ones are mentioned in the following list :—

1. Quartz, opal, chalcedony.
2. Calcite, aragonite.
3. Zeolites.
4. Iron oxides.
5. Chlorite.
6. Talc.
7. Muscovite.
8. Serpentine.
9. Epidote (Pistazite).
10. Leucoxene.
11. Kaolin, etc.

The Law of Mineral Combination.—The more important original constituents of igneous rocks may be grouped as follows :—

1. *Felspathic Silicates:* Felspars and Felspathoids.
2. *Ferromagnesian Silicates:* Pyroxene, Amphibole, Biotite, Olivine.
3. *Free Silica:* Quartz.

4. *Accessory Minerals:* Magnetite, Ilmenite, Hæmatite, Apatite, Rutile, Zircon, Sphene, etc.

The members of these several groups combine according to a somewhat definite plan, which may be termed the law of mineral combination. Thus, in igneous rocks,* one or more members of the first group (*Felspathic Silicates*) are associated with one or more members of the second group (*Ferromagnesian Silicates*). With these are more sparingly associated members of the fourth group (*Accessory Minerals*); while *Free Silica* may or may not be present.

Classification of Crystalline Igneous Rocks

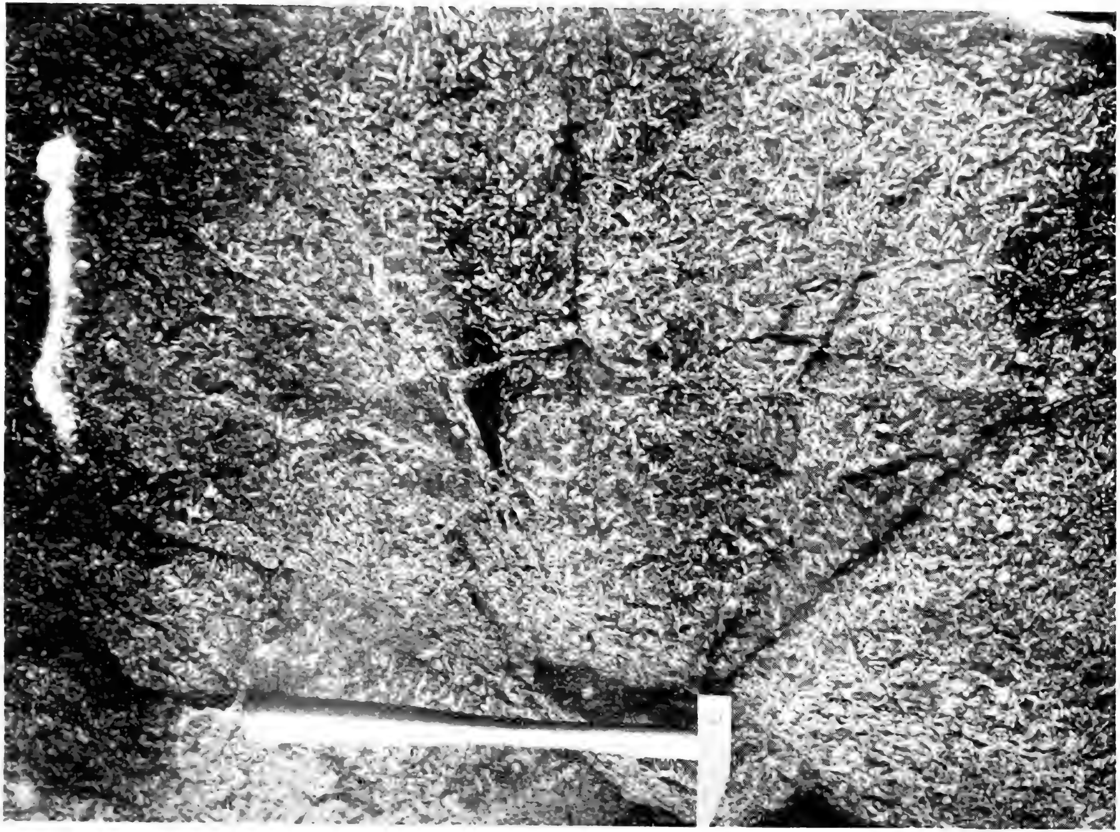
No quite satisfactory classification of these rocks is at present possible. From the chemical point of view they have been grouped according to the percentage of silica they contain, as *acid*, *neutral* or *intermediate*, and *basic*, but there are so many gradations from the one type into the other that this arrangement breaks down when we come to apply it. We find, for example, that certain rocks of the same general character, and which obviously constitute a family, are under this chemical classification divided instead of being grouped together. Some andesites, for instance, would be termed intermediate, while others would be described as basic. Perhaps a nearer approach to a satisfactory classification is reached by taking into consideration the mineralogical constitution of the rocks, and arranging them according to the character of their dominant ingredients. This arrangement does not in effect differ much from that which is based on the silica percentage, but it has at least the negative merit of not separating closely allied types of rock.

The most important rock-forming minerals are undoubtedly the felspars. In the great majority of eruptive rocks they play a prominent rôle, since a large number have alkali felspar as their chief constituent, while another considerable division is characterised by the presence of soda-lime felspar as the dominant ingredient. In the remaining types of rock, felspar is either absent or plays the subordinate part of an occasional accessory mineral. In one division of those rocks, felspathoids (nepheline, leucite, etc.) take the

---

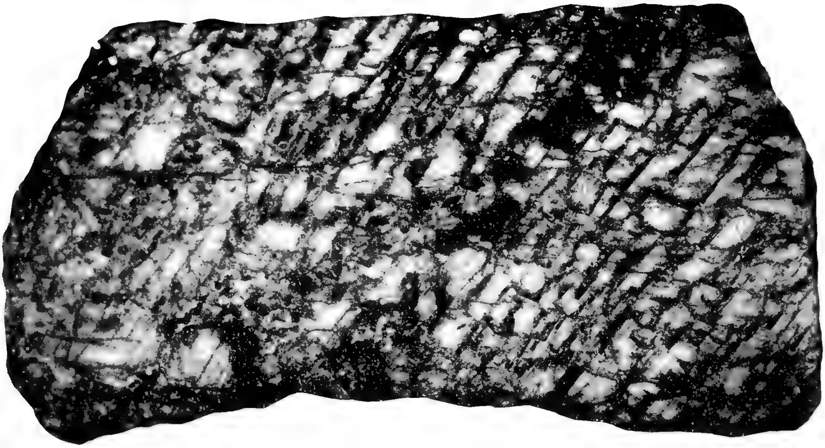
* With the exception, of course, of the ultra-basic rocks, which contain neither felspars nor felspathoids,

PLATE X.

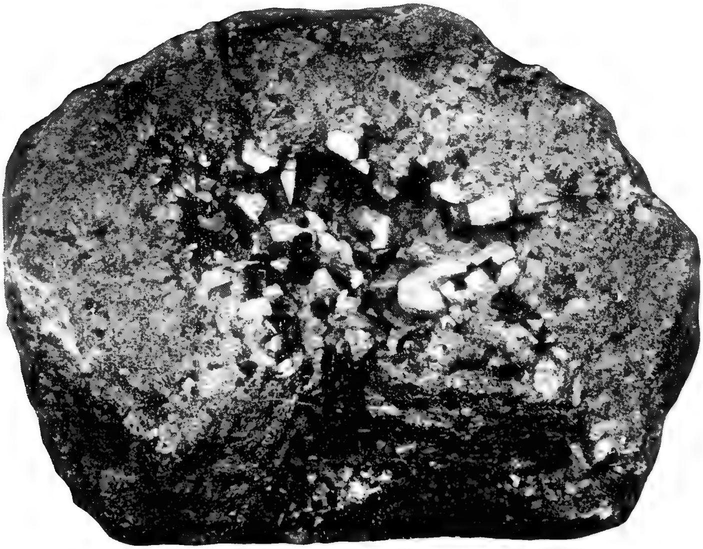


Porphyritic Structure (Diabase Porphyrite), Lendalfoot, Ayrshire.

From Geol. Surv. Memoir, "The Silurian Rocks of Britain," Vol. I., Scotland.



1. GRAPHIC GRANITE. About natural size.



2. DRUSE OR GEODE IN GRANITE. Nearly natural size.

[*Between pages* 40 *and* 41.

place of felspar, while in the other neither felspars nor felspathoids are present.

I. ROCKS WITH DOMINANT ALKALI FELSPAR

This group includes the granites, quartz-porphyries, and rhyolites—all acid rocks with a percentage of silica ranging up to 80, and the syenites, trachytes, and phonolites—intermediate rocks with a silica percentage ranging up to 70 or thereabout. They exhibit all kinds and degrees of texture and structure, some being crystalline, others hemicrystalline, and yet others essentially vitreous. As a rule, the coarse-grained holocrystalline types are of deep-seated origin, while the finer grained microgranitic and porphyritic types are usually hypabyssal. Many of these finer grained holocrystalline rocks occur as dykes, veins, and sills. The hemicrystalline and vitreous types have as a rule flowed out as lavas, or have consolidated as intrusive rocks not far from the surface.

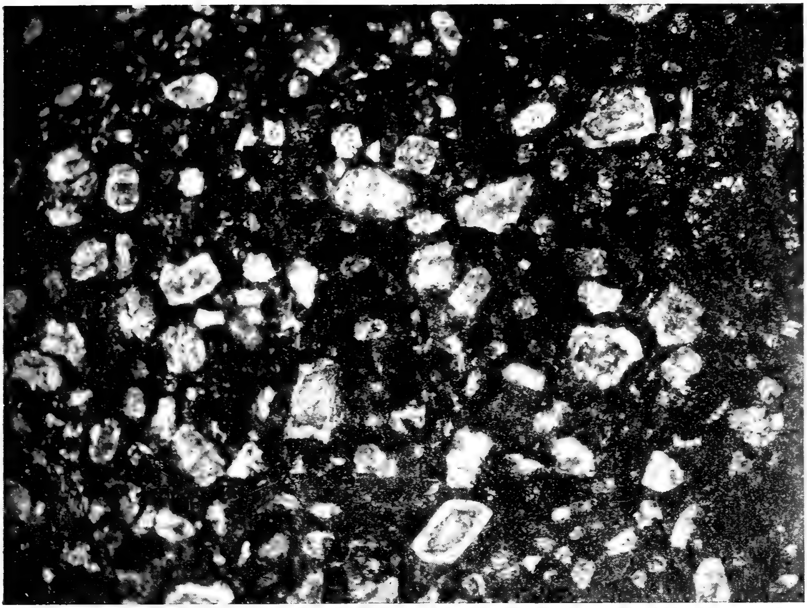
Granite is a holocrystalline aggregate of quartz, alkali felspar (orthoclase and microcline, usually accompanied by some plagioclase), and a ferromagnesian mineral (mica or hornblende), the constituents occurring as crystalline granules of approximately similar size (= *granitoid* structure). The rock varies in texture from microcrystalline to very coarsely crystalline. The colour, which largely depends on that of the felspar, is usually light or dark grey or reddish; occasionally it is greenish. In coarse or medium grained granite the essential minerals are readily distinguished. The felspar appears opaque, and is sure to show some of its crystal faces and cleavage-planes with their vitreous or pearly lustre. The quartz, on the other hand, is quite irregularly outlined. It is usually dark grey but transparent, and shows a kind of glassy lustre on its uneven broken surfaces; there is no trace of cleavage. The mica occurs in lustrous plates and scales which are readily separated into the thinnest lamellæ. The hornblende is recognised by its dark green colour and its common prismatic or columnar appearance. Accessory minerals may or may not be numerous, some of the commonest being apatite, sphene, zircon, magnetite, etc.

A few varieties of granite may be mentioned—only the essential minerals being named :—*Normal* or *Muscovite-granite* = felspar + quartz + muscovite + biotite ; *Granitite* or *Biotite-granite* (Plate IV. 3) = felspar + quartz + biotite ; *Hornblende-granite* = felspar + quartz + hornblende, and usually some biotite ; *Tourmaline* or *Schorl-granite* = felspar + quartz + schorl ; *Graphic granite* = felspar + quartz, which have crystallised together, the quartz assuming the form of successive irregular columnar shells, arranged in parallel positions, and enclosed in the felspar (see Plate XI. 1). This is known as *pegmatitic* structure ; when seen in cross-section it has some resemblance to Hebrew writing, hence the name *graphic*. While this structure often occurs megascopically, especially in coarsely crystalline veins associated with granite, it is sometimes only to be detected under the microscope = *micropegmatite* (Plate VIII. 3). *Giant-granite* or *Pegmatite* = any very coarse-grained granite—granites of this kind very frequently show pegmatitic structure ; *Aplite* or *Haplite* = a fine-grained granite containing little or no mica, met with as veins ; *Greisen* = a granite with little or no felspar, occurring as veins in normal granite ; *Porphyritic granite* = a rock showing large phenocrysts* of felspar, disseminated through a relatively fine-grained granitoid matrix ; *Granite-porphyry* or *Microgranite* = a rock consisting of a microgranitic or micropegmatitic (*granophyric*) groundmass, with phenocrysts of felspar, quartz, pyroxene, and occasionally amphibole ; it occurs sometimes forming a part of a large mass of ordinary granite : at other times it forms dykes and veins proceeding from granite ; *Granite-gneiss* = a granite in which the minerals have in whole or in part a rudely parallel arrangement, giving to the rock a coarsely banded structure.

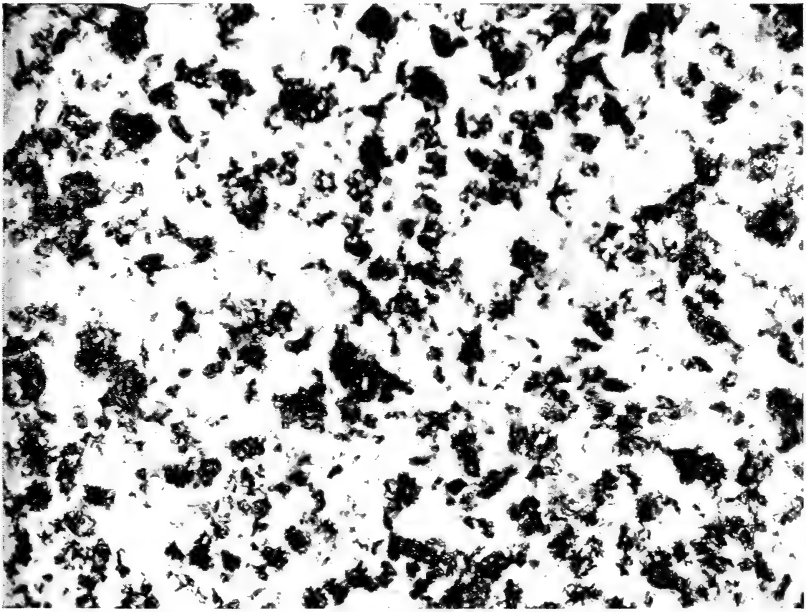
Structures in granite :—*Geodes* and *drusy cavities :* these are irregular cavities which often occur sporadically in granite, and are usually lined with finely crystallised, well-formed examples of the essential and accessory ingredients of the rock (see Plate XI. 2). The felspars and the quartz are generally conspicuous, and with these mica and one or more of the accessory ingredients, as sphene, apatite, zircon, topaz, beryl, etc. *Secretions :* these are of two kinds—basic and acid. The *basic secretions* are dark masses of very irregular form and varying size, rich in ferro-magnesian minerals (biotite, hornblende), sphene, and iron ores. They often resemble fragments broken from some other rock, and subsequently enclosed in the granite. Possibly they may be fragments of massive aggregates of basic ingredients which may have crystallised out from the magma at an early stage in the process of consolidation, and become broken up during subsequent movements of the slowly cooling and consolidating plutonic mass. The *acid secretions* are light-coloured,

---

* The origin of such phenocrysts is not yet understood. The explanation which is supposed to account for the formation of phenocrysts in lava-form rocks (see *supra*, p. 35) can hardly apply to the phenocrysts of plutonic rocks, which cooled at great depths, and therefore under the continuous pressure of heavy overlying rock masses.



1. Porphyritic Structure. Quartz-porphyry. Natural size.



2. Granitoid Structure. Tonalite. Natural size.

[*To face page* 42.

coarse or fine-grained streaks and veins, poor in ferromagnesian constituents. These veins often look as if they occupied fissures or clefts. Such fissures may be supposed to have originated while the plutonic mass was only in part solidified—the still mobile, residual, acid magma having been squeezed into clefts in the solidified portions during movements of the gradually cooling rock. The granites are among the most widely distributed of eruptive rocks. Although most are of deep-seated origin, yet a few appear to have been intruded at a less depth from the surface.

Quartz-porphyry.—This is a hemicrystalline rock. The groundmass is sometimes composed of a microgranitic aggregate of quartz and felspar (chiefly orthoclase), at other times it is cryptocrystalline. Thus, to the naked eye the groundmass in some cases appears very finely crystalline, and in other cases dense and smoothly compact. Scattered through the groundmass are numerous phenocrysts of quartz and felspar (either or both), together with a ferromagnesian mineral (biotite or hornblende). The felspar is usually orthoclase, but plagioclase (chiefly oligoclase) is often associated with it (see Plate XII. 1). The quartz not infrequently occurs in the form of corroded bi-pyramidal crystals, and often contains inclusions of the groundmass. The colour of the rock depends largely upon that of the orthoclase, which is often exceedingly abundant, and may be red or white. Accessory minerals are also numerous, such as apatite, sphene, zircon, magnetite, etc. As the quartz-porphyries are mostly very old rocks, *secondary* minerals are generally present, especially kaolinite, chlorite, epidote, and muscovite. *Granophyre* is a quartz-porphyry, the groundmass of which consists of a micropegmatitic intergrowth of quartz and felspar (see Plate IX. 1). The quartz-porphyries, like the granites, are very widely distributed.

Rhyolite (*Liparite; Quartz-trachyte*).—This rock is usually somewhat light-coloured — grey, yellowish, reddish, or greenish. It is hemicrystalline—the groundmass varying considerably in character in one and the same rock. Sometimes it is glassy for the most part, or it may be cryptocrystalline, or microcrystalline. Scattered throughout are phenocrysts of sanidine, plagioclase, quartz, biotite, and occasionally hornblende or augite.

Under the microscope what seems to be a thoroughly compact groundmass is sometimes resolved into an intimate aggregate of lath-shaped microlites of sanidine, often fluidally arranged, entangled among which are frequently seen crystalline granules of plagioclase, quartz, zircon, magnetite, apatite, etc. In other cases, however, the apparently compact groundmass is found to be composed largely of glass or of cryptocrystalline matter, or both, and usually exhibits perlitic, spherulitic, and fluxion structures. Occasionally the phenocrysts are so large and so abundant that in hand-specimens little or no groundmass can be seen, and the rock assumes a granitoid aspect. In other cases, when phenocrysts are sparingly present or wanting, the mass has a porcellanous or enamel-like appearance, with a somewhat waxy lustre. All these varieties of texture and structure may occur in one and the same lava-flow—lenticular streaks, laminæ, and layers of coarser and finer grained, of lighter and darker materials alternating. Frequently the rock exhibits a finely porous or cellular structure, and occasionally spherical, flattened, and irregular shaped cavities appear, which may be encrusted or filled with quartz, opal, jasper, chalcedony, etc. Probably these siliceous minerals were deposited by chemical processes before the rock had completely cooled and solidified. *Felsite* is the name given to a fine-grained to compact rock, throughout which are scattered phenocrysts of orthoclase, plagioclase, quartz, and ferromagnesian minerals. It is simply a more or less altered rhyolite, quartz-porphyry, or vitreous rock. Under the microscope it shows either a microcrystalline or cryptocrystalline texture. Spherulitic and perlitic structures are often present.

Rhyolites have a somewhat wide distribution. The freshest kinds are of Tertiary age, and are sparingly represented in the British Islands ; they occur chiefly in Ireland (Antrim, co. Down) ; but the altered kinds are common among our Palæozoic rocks, occurring both lava-form and intrusive.

Pitchstone and **Obsidian**.—These represent the vitreous condition of acid rocks—they are hardly, therefore, independent rock-species, for they very often occur as the superficial crusts of hemicrystalline acid rocks. They contain some 73 per cent. of silica. **Pitchstone** is usually dark green or black, but lighter green, red, brown, yellow, and even white varieties occur. The lustre of the rock is pitch-like or resinous ; the fracture usually conchoidal, but often irregular or splintery. Sometimes it contains very few crystallites or microlites—at other times it is crowded with such inclusions — the microlites occasionally forming skeleton-crystals, as in the well-known Arran pitchstone, where they are feather-like and dendritic (see Plate VII. 1). Phenocrysts now and again abound ; they are commonly either quartz

2. Banded Obsidian. Natural size.

1. Spherulitic Obsidian. Natural size.

[To face page 44.

(Plate IV. 4) or an acid felspar or both; green augite also is often present, and not infrequently biotite or hornblende; less common are rhombic pyroxenes. *Pitchstone-porphyry* is the name given to this rock, when the phenocrysts are numerous and prominent. **Obsidian** (see Plate XIII.) is grey to dark grey and black, seldom red or brown. The lustre is vitreous, and the fracture conchoidal. Phenocrysts are not common—quartz rarely or never appearing. Sometimes this glass is crowded with crystallites, spherulites, microlites, etc.; in other cases the rock is almost devoid of such bodies.

The structures characteristic of glassy rocks have already been described (p. 34). *Perlite* is a glass characterised by the prevalence of perlitic structure, just as *Spherulite-rock* is so named from the abundant development of spherulitic structure. *Pumice* is a frothy, foam-like, stringy, cellular, spongiform acid glass: it does not form individual rock-masses, but occurs as a crust on acid lavas, or as loose blocks, scoriæ, cinders, etc. When a glassy rock becomes crowded with crystallites, spherulites, and microlites, it acquires a stony aspect, and is said to be *devitrified.*

Obsidian is usually associated with effusive rhyolites—into which indeed it frequently passes. It occurs in Hungary, the Lipari Islands, the Canary Islands, Iceland, the Western United States, Mexico, Ecuador, New Zealand, etc. Pitchstone is also somewhat widely distributed, occurring in various parts of Germany, Tyrol, N. Italy, Scotland, etc.; it appears commonly in the form of dykes and intrusive sheets or sills.

The rocks described in the foregoing pages are all acid rocks, having a similar chemical composition, and their different and often strongly contrasted petrographical aspect would appear, therefore, to be due to the varying conditions under which they cooled and solidified. Rapid cooling of molten matter, as we have seen, results in the production of a vitreous rock, while protracted cooling gives rise to a hemi-crystalline or even a holocrystalline type. Geologists, therefore, look upon granite as the deep-seated equivalent of our acid lavas, or rhyolites and rhyolite-glasses or obsidian. But between the deep-seated plutonic granites and the volcanic rhyolites, occur rocks which are to some extent intermediate in character—that is to say, they are not quite so crystalline as granite, and not usually so vitreous as the rhyolites and obsidians; these are the quartz-porphyries. Thus the same molten matter, if it were poured out at the surface, would solidify as an obsidian or a rhyolite; if it cooled at a very considerable depth it would consolidate into granite; while if it were injected in the form of sills and dykes at a less depth, some portions might become microgranite or quartz-porphyry, and others, which had cooled more rapidly, pitchstone.

Syenite, usually reddish but not infrequently grey, is a holocrystalline granitoid aggregate of orthoclase and a ferromagnesian mineral, which may be hornblende, augite, or mica. Syenite is differentiated from granite by the absence of quartz. Nevertheless, under the microscope a little quartz can often be seen straggling among the other ingredients. The accessory minerals include plagioclase, which is rarely quite wanting, apatite, zircon, sphene, ilmenite, magnetite.

Normal Syenite consists essentially of orthoclase and hornblende. *Augite-* or *Pyroxene-syenite* contains orthoclase and plagioclase, augite (sometimes diallage), hypersthene, biotite, and a little quartz. When the chief ferromagnesian mineral is biotite, we have the variety known as *Mica-syenite*. *Elæolite-syenite* is a compound of alkali felspar, elæolite, and one or more ferromagnesian minerals (pyroxene, amphibole, mica). The rock is noted for the variety of its accessory ingredients, amongst which are plagioclase, sphene, apatite, zircon, fluor-spar, sodalite, and others.

The syenites are not so widely distributed as the granites. The type-rock is that of the Plauenscher-grund, Dresden. Many varieties of syenite occur in S. Norway, and have received special names (*Laurvikite*, *Nordmarkite*, etc.). *Kentallenite* is the name given to a basic syenite occurring in Argyllshire.

Orthoclase-porphyry (*Orthophyre*) is a grey, brown, or reddish rock, the groundmass of which consists essentially of microcrystalline orthoclase. Scattered through this are phenocrysts of orthoclase. Plagioclase is sometimes present, and needles of hornblende, scales of biotite, or granules of augite, may often be observed; a little quartz, too, occasionally appears. The most conspicuous ingredient, however, is the orthoclase.

When ferromagnesian minerals, such as biotite, are plentifully present, this rock passes over into **Minette** or *Syenitic Mica-trap*. This rock, when fresh, is dark grey to black, but owing to weathering it is often brown. The texture is medium to fine-grained or compact. The microscope shows, however, that it is holocrystalline.

Here also may be included *Bostonite*, a light yellowish or grey rock, with a fine-grained to compact groundmass, composed chiefly of small lath-like crystals of felspar (see Plate IX. 3). Dark ferromagnesian minerals are very sparingly present. The rock occurs in dykes, and is associated with alkali-granites, alkali-syenites, and elæolite-syenites. Orthoclase-porphyry is not so common a rock as quartz-porphyry. It occurs in S. Scotland, where it is associated with volcanic rocks of Old Red Sandstone age.

Trachyte is a hemicrystalline rock, usually light or dark grey or yellowish, but sometimes brownish or even reddish. The texture of the groundmass is commonly close-grained, apparently sometimes compact; frequently, however, it has a rough, porous structure. Disseminated through it, phenocrysts are usually conspicuous, especially sanidine, in addition to which plagioclase, hornblende, biotite, and pyroxene frequently occur.

Under the microscope the groundmass would appear to consist essentially of lath-like microlites of sanidine, frequently showing fluxion structure, and often entangling a few granules of a ferromagnesian mineral, which is usually augite (see Plate IX. 4). Some interstitial glass or microfelsitic matter may be present. Accessory minerals are numerous, amongst them being apatite, magnetite, zircon, sphene; while in certain trachytes, sodalite and olivine occasionally make their appearance.

The glassy varieties of trachyte are known as *Trachyte-obsidian* and *Trachyte-pitchstone*, and so closely resemble the rhyolitic glasses that they can hardly be distinguished from these except by chemical analyses. They contain a lower percentage of silica (about 62).

Trachyte is one of the commonest effusive rocks of Tertiary and later age—occurring in most volcanic districts in the old and the new worlds. Trachytes, however, are not exclusively young rocks; rocks of this type occur among the Old Red Sandstone and the Carboniferous volcanic series of Scotland.

Phonolite is a greenish or greyish to white or yellow, and sometimes brown rock composed essentially of sanidine and nepheline or leucite (either or both). The texture is usually compact, with a somewhat greasy lustre, or it may be fine-grained with dull lustre. The most conspicuous phenocrysts are sanidine and nepheline (or leucite), besides which the unassisted eye may often distinguish pyroxene or amphibole. The rock is characterised by the absence of quartz, by its somewhat flaggy structure, by its conspicuous crystals of sanidine, and by the bell-like clink it gives out when struck with the hammer.

The microscope proves the groundmass to consist of microlites and small crystals of sanidine and nepheline (or leucite), which not infrequently show parallel arrangement—a structure to which probably the flaggy structure of the rock is in some measure due. Interstitial glass is rarely present. The microscope reveals many other minerals besides those of macroscopic size, such as the common accessories, sphene, zircon, etc.; while one or more of the following may be present: biotite, amphibole, pyroxene, black garnet, sodalite, haüyne, or nosean, etc. *Leucite-phonolite* is a phonolite in which leucite takes the place of nepheline; when haüyne occurs instead of nepheline we have *Haüyne-phonolite.* When leucite largely takes the place of sanidine the rock is known as *Leucitophyre.* In the vacuoles, fissures, etc., of all phonolites, zeolites and calcite are of common occurrence.

The syenites play much the same part as the granites—occurring as more or less deep-seated plutonic rocks—while orthoclase-porphyry and minette are also intrusive, but appear chiefly in the form of sills and dykes. The trachytes may be looked upon as the effusive or volcanic representatives of ordinary syenites; while the phonolites, in like manner, may be the effusive equivalents of the plutonic elæolite-syenites.

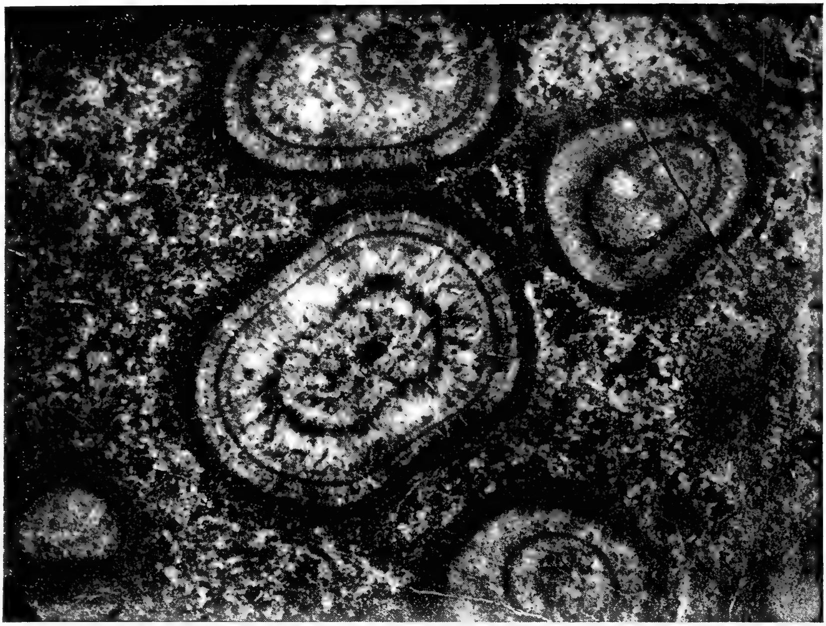
2. Rocks with Dominant Soda-lime Felspar

This group includes some of the so-called "intermediate" types (diorites and andesites), and others which are on the whole more basic (gabbros, dolerites, and basalts). Like the rocks of the preceding division, they are holocrystalline, hemicrystalline, and vitreous.

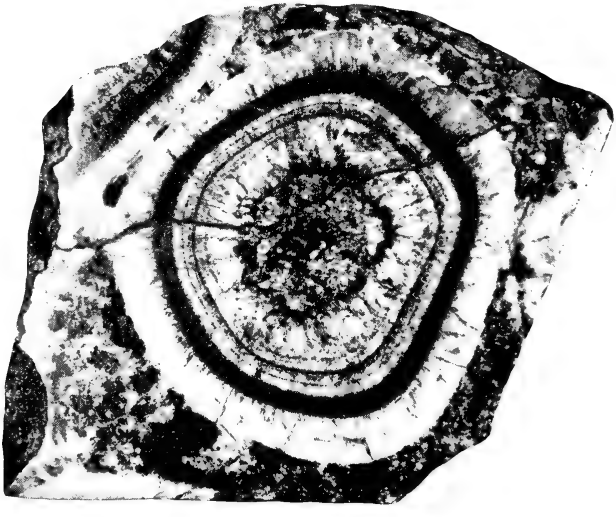
Diorite is a holocrystalline aggregate of plagioclase and a ferromagnesian mineral which may be hornblende, biotite, augite, or enstatite. The rock varies in texture from granitoid to compact—the granitoid varieties being speckled green and white, while the compact kinds are often dark green. Accessory minerals are—apatite, magnetite, sphene, zircon, etc.

The following varieties are recognised:—*Quartz-diorite* = quartz + plagioclase + hornblende or biotite, or both. [It may be noted that a little quartz may be present in any diorite.] *Mica-diorite* = plagioclase + biotite, and *Augite-diorite* = plagioclase + augite—in both these varieties hornblende is often present. *Tonalite* (Plate XII. 2) is a quartz-mica-diorite, containing some orthoclase, and approaching hornblende-granite. Many diorites are conspicuously porphyritic. *Corsite* (Orbicular Diorite) is a rock in which the constituents have crystallised together so as to form spherical aggregates having a concentric radiate structure (Plate XIV.). *Kersantite* is a dioritic mica-trap composed essentially of plagioclase and biotite. The diorites, although widely distributed, are not very abundant. They occur chiefly as intrusive masses or as dykes and veins.

Andesite is a hemicrystalline rock, usually dark coloured grey to brown. It consists essentially of plagioclase with a



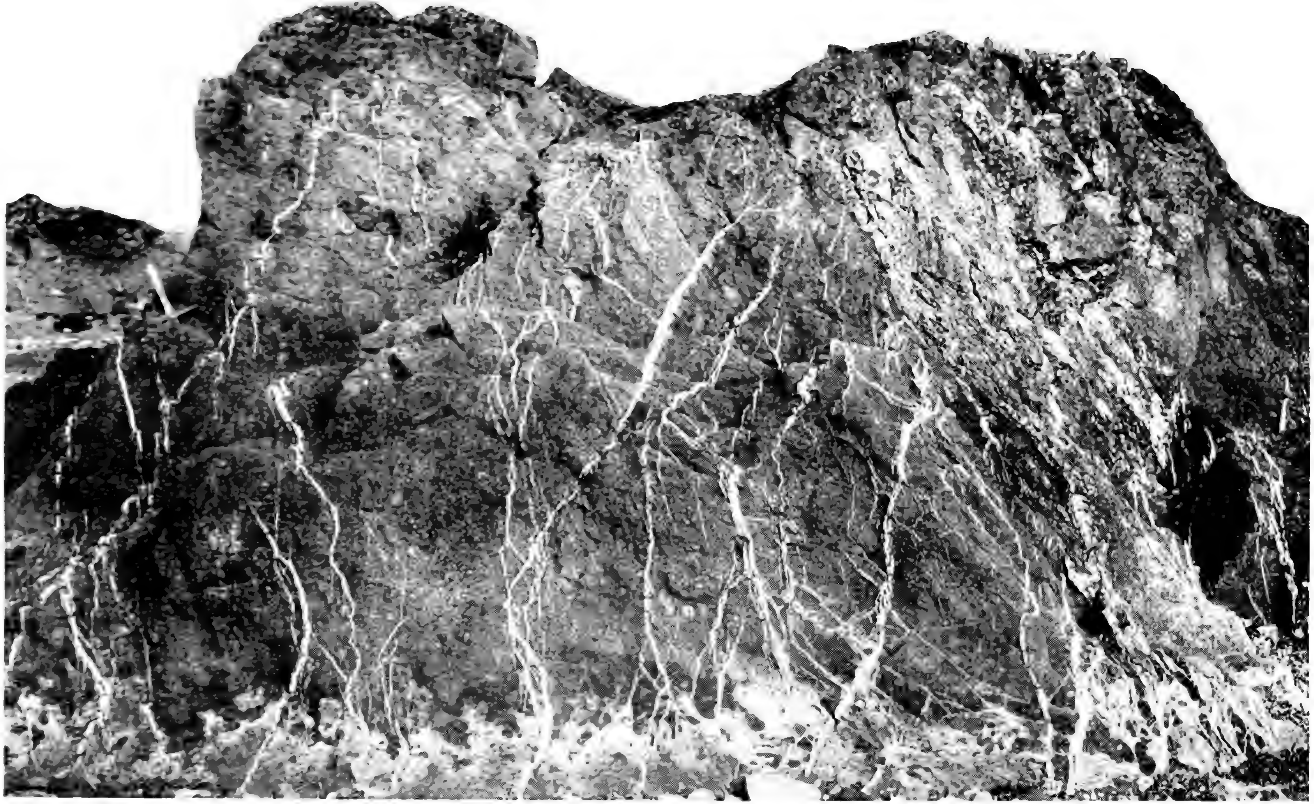
1. ORBICULAR DIORITE (CORSITE, NAPOLEONITE). Nearly natural size.



2. THE SAME. Natural size.

[*To face page* 48.

PLATE XV.



Volcanic Tuff, veined with Calcite, Shore, West of Kincraig Point, Elie, Fife.

Photo by H.M. Geological Survey.

[*To face page* 49.

ferromagnesian constituent—biotite, augite, hornblende, or hypersthene—very often two or more of these being present. According to the nature of the predominant ferromagnesian constituent, the rock is termed *Biotite-*, *Hornblende-*, *Augite-*, or *Hypersthene-andesite.* Many andesites are more or less markedly porphyritic—the phenocrysts being usually plagioclase, and one or more of the ferromagnesian minerals. (See Plate III. 3.)

Under the microscope the groundmass consists of lath-like microlites and crystals of plagioclase, usually fluidally arranged, with minute granules of ferromagnesian minerals, magnetite, etc., and with or without residual glass. In augite- and hypersthene-andesites the groundmass is often vitreous. When the whole rock is glassy it is known as *Andesitic Obsidian* or *Andesitic Pitchstone.* Amongst the accessory minerals in andesites are apatite, magnetite, sanidine, garnet, sphene, olivine, zircon, etc. *Dacite* contains quartz in addition to the essential ingredients of an andesite. The andesites are well represented in the Tertiary and later volcanic districts of Europe and America. More or less altered or decayed andesites are very common in the British Islands. In these rocks (formerly known as *Porphyrites*) the felspar is often kaolinised, while the augite and hornblende may be partially or wholly converted into chlorite, the hypersthene changed into bastite (a fibrous mineral with much the same composition as serpentine), and the magnetite into hæmatite.

Gabbro is a granitoid holocrystalline aggregate of plagioclase (basic soda-lime felspar) and a ferromagnesian silicate, the texture ranging from fine-grained to very coarsely crystalline. Several varieties are recognised, the distinguishing character of each being the particular ferromagnesian constituent that happens to be present. Thus normal *Gabbro* = plagioclase + diallage ; *Norite* = plagioclase + hypersthene ; *Olivine-gabbro* and *Olivine-norite* contain olivine in addition to their essential ingredients ; *Hornblende-gabbro* = plagioclase + pyroxene (diallage or hypersthene) + hornblende ; *Mica-norite* = plagioclase + hypersthene + biotite ; *Troctolite* = plagioclase + olivine. Amongst accessory ingredients in all the gabbros are apatite, magnetite, ilmenite, garnet, rutile, spinelloids, etc. The gabbros have a mottled or speckled aspect, the felspar being usually bluish-white to grey, and the ferromagnesian mineral generally dark green.

The gabbros are usually more or less altered, the felspar being frequently changed into saussurite, and the pyroxene into smaragdite and actinolite. The pyroxenes (diallage and hypersthene) almost invariably exhibit a characteristic pearly or submetallic lustre (=*schillerisation*), due to the development of thin brown films along their cleavage-cracks. The gabbros are widely distributed, occurring as plutonic masses, sills, and dykes.

Dolerite is for the most part holocrystalline, and varies in texture from medium-grained to coarsely granular. The chief constituents are plagioclase, augite, and iron-oxides. Occasionally, some interstitial glass may occur. Olivine, hypersthene, biotite, hornblende or quartz may be present, and thus give rise to varieties, as *Olivine-dolerite*, *Hypersthene-dolerite*, *Mica-dolerite*, etc.

The plagioclase usually occurs as well-formed crystals and microlites, which penetrate or are enclosed as endomorphs in the ferromagnesian mineral (augite or olivine). This is known as *ophitic* structure (see Plate VIII. 4). Quartz, when present as an original constituent, is usually devoid of crystallographic form, but is sometimes intergrown with the felspar=*micropegmatitic* or *granophyric* structure.

The common accessory ingredients are magnetite, ilmenite, and apatite. Dolerite is a dark coloured rock, the medium grained types being almost black when fresh, while the coarser grained varieties are speckled dark green (or black) and white (or pale pink). Owing to decomposition of the ferromagnesian constituents, however, many dolerites have a dull, dark greenish colour. Rocks of this altered type are known as *Diabase.* In these the plagioclase is often altered into an aggregate of granules of epidote, calcite, kaolin, etc., while the ferromagnesian minerals are usually largely replaced by chlorite, serpentine, etc., and the ilmenite more or less changed into leucoxene (titanite). Dolerite (Diabase) occurs usually in bosses, sills, and dykes, and is very widely distributed.

Basalt.—This is a greyish-black to black, heavy rock, so compact, as a rule, that the mineral constituents cannot be recognised by the naked eye. Frequently, however, small phenocrysts are present, some basalts being markedly porphyritic with such minerals as plagioclase, augite, and olivine.

Microscopic examination shows that the rock consists of an aggregate of small crystals and crystalline granules of plagioclase, augite, and usually olivine (see Plate IV.). Almost constant accessories are magnetite and ilmenite. Interstitial glass is frequently present, plentifully or meagrely as the case may be. Amongst the accessory minerals occasionally present, we may note biotite, hornblende, and hypersthene, each, when prominent, giving rise to a variety of the rock, as *Mica-*, *Hornblende-*, and *Hypersthene-basalt*. Olivine is sometimes wanting; occasionally it occurs in rounded granular aggregates which may reach the size of a man's head. Such aggregates are often rich in pyroxenes and spinelloids.

Basalt is abundantly met with as an intrusive rock in the form of sills and dykes, and as an effusive rock or lava. Like all lavas, effusive basalt is often more or less vesicular and slaggy, the amygdaloidal cavities being lined and filled with such minerals as zeolites, quartz, chalcedony, calcite, etc.

Tachylite is a basalt-glass which is sometimes smoothly homogeneous and compact, and at other times highly porous and vesicular. *Basalt-pumice* is either foam-like or spongiform, or may be drawn out in the form of hair-like threads containing long, cylindrical, gas pores. Tachylite sometimes occurs as a vesicular crust on certain basalt-lavas, the basal portions of which are also often highly vitreous. The same dark glass not infrequently forms the external surface of basalt-dykes—this "chilled edge" varying in thickness from a few lines to several inches.

The diorites seem to be the plutonic equivalents of the effusive hornblende-, mica-, and quartz-andesites (dacites). These andesites, however, also occur intrusively. The effusive augite-andesites, and the basalts, on the other hand, being more basic, are closely related to the intrusive dolerites and gabbros. It will be remembered, however, that basalt often occurs intrusively, and the same is the case with augite-andesite.

3. ROCKS WITH FELSPATHOIDS TAKING THE PLACE OF FELSPARS

The only rocks belonging to this group that need be mentioned are Nepheline-basalt and Leucite-basalt, both of which are effusive rocks of relatively recent geological age, and having a rather limited distribution.

Nepheline-basalt is black, and composed essentially of nepheline, augite, and olivine, with magnetite, apatite, biotite, and haüyne as common accessories. Glassy base is occasionally present. Some varieties are as compact and fine-grained as typical plagioclase-basalt, from which in hand-specimens they can hardly be distinguished; others have a doleritic aspect. Phenocrysts of olivine and augite are often more or less conspicuous.

Leucite-basalt, dark grey to black, has for its essential constituents leucite, augite, and olivine. Amongst the accessory ingredients are nepheline, biotite, hornblende, haüyne, apatite, magnetite, etc. The rock is fine-grained, and usually shows phenocrysts of augite or olivine or both. Little or no glassy base is present.

There are several other rocks included in this division, amongst which are *Nephelinite* = augite + nepheline ; *Leucitite* = augite + leucite.

4. ROCKS WITHOUT FELSPARS OR FELSPATHOIDS

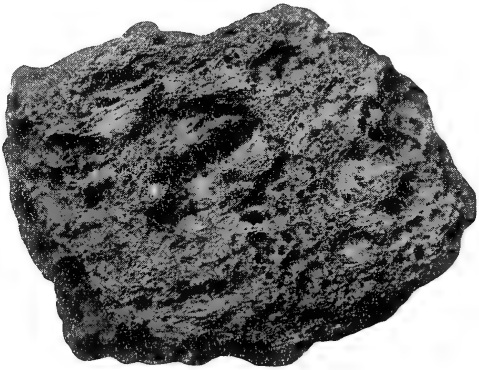
These are dark coloured, heavy, ultra-basic rocks—the silica percentage hardly averaging more than 43, while the specific gravity ranges between 2·7 and 3·5.

Limburgite (*Magma-basalt*) is a reddish-brown or dark grey to black rock, composed essentially of augite and olivine set in a glassy base. The rock is either fine-grained or compact, with a pitch-like lustre. Under the microscope it is seen to consist largely of glass, which, however, is sometimes so crowded with microlites of augite, magnetite, etc., that little or no glass may be visible. Phenocrysts of olivine and augite are usually conspicuous. Amongst the accessory ingredients are magnetite, ilmenite, biotite, hornblende, haüyne, etc. **Augitite** is a black rock composed essentially of augite and magnetite in a glassy base, and resembles limburgite, from which, however, it is distinguished by the absence of olivine. Neither of these rocks is important so far as its distribution is concerned. The former takes its name from Limburg, near the Kaiserstuhl in Baden, and is met with in various other places in Germany. It occurs also in southern Sweden, Spain, the Canary Islands, and in Central Scotland. Augitite is found in Bohemia, Central France, the Canary Islands, the Cape Verd Islands, and Ireland.

Peridotites.—These are the most basic of igneous rocks, and are composed mainly of olivine—hence often designated "olivine-rocks." With this constituent are associated small proportions of one or more of the following minerals—picotite, chromite, augite, diallage, hornblende, biotite, enstatite, apatite, magnetite, ilmenite, garnet, etc.

A number of varieties have been described, of which the following may be mentioned :—*Dunite*, composed almost wholly of olivine with a little picotite or chromite—occurs in the Dun Mountain, S. New Zealand ; *Picrite*, a rock rich in idiomorphic olivine, with which are associated in varying amount pyroxene (augite, hypersthene, enstatite), hornblende, biotite, magnetite, ilmenite, apatite, and not infrequently a little plagioclase. According to the relative predominance of augite, hornblende,

1. Scoria or Cinder (Grand Canary). About half natural size.



2. Scoria or Cinder (Teneriffe). About natural size

[*To face page* 52.

enstatite, or biotite, we have augite-, hornblende-, enstatite-, or mica-picrite; the picrites are sparingly represented in the British Islands; *Lherzolite* (from L'herz in the Pyrenees) = olivine + enstatite + light green pyroxene, with some accessory spinelloid and a little magnetite and apatite.

The magma-basalts are volcanic rocks, mostly of late Tertiary age, occurring, like ordinary basalt, both effusively and intrusively. The peridotites are usually intrusive, and closely related to the dolerites and gabbros, into which they graduate by the increase of felspathic constituents. Bosses of gabbro and dolerite are not infrequently bordered by olivine-rock, into which they pass—the two kinds of rock obviously being different phases of one and the same intrusive mass.

The olivine-rocks are often highly serpentinised—the olivine being more or less readily altered. Thus many massive serpentines are merely highly altered igneous rocks (see p. 23).

B. Fragmental Igneous (Pyroclastic) Rocks

These rocks include the various kinds of material which have been ejected from volcanoes in the form of blocks, scoriæ, lapilli, bombs, sand, and ash. **Blocks** and **Lapilli** are the names given to the larger and smaller rock-fragments, which may be angular or subangular; while the finer grained materials are known as **Sand** and **Ash.** **Scoriæ** are loose pieces of cindery lava (Plate XVI.). **Bombs** are elliptical or pear-shaped fragments, often vesicular or hollow (see Plates XVII., XVIII.). They are simply clots torn from the surface of a mass of molten rock by the explosive energy of steam, and ejected from the crater of a volcano, their form being doubtless the result of their rotatory motion. Accumulations of these and other kinds of volcanic ejecta frequently become indurated, and are met with in regular and irregular beds associated with crystalline igneous rocks of all geological periods. **Volcanic Agglomerate** is the name given to a coarse admixture of large and small blocks and stones set in a matrix of comminuted rock débris and grit, which may be either abundant or meagre. Frequently, this rock is found occupying the pipes or throats of ancient volcanoes—the upper portions of which have been denuded away.

Volcanic Breccia is a mass composed of angular fragments of volcanic rock. **Volcanic Tuff** is the name given to aggregates of the finer grained ejectamenta (Plates XV.; XX. 1). These are often arranged in layers and beds which have been spread out by water action. There are endless varieties of structure and texture—some tuffs consisting of lapilli, or of grit, or of sand and ash; others made up of all four, and not infrequently arranged in lenticular layers and beds. Some volcanic tuffs consist of the finest ash-like material, forming a dull, fine-grained or compact rock, which varies in colour from white or grey, to darker or lighter shades of red, blue, yellow, etc.

As tuffs are composed almost exclusively of fragments and the comminuted débris of lava, they naturally differ in character according to that of the rocks from which they have been derived. Hence we have *basalt-tuff*, *andesite-tuff*, *rhyolite-tuff*, etc., any of which may of course contain a large or small proportion of fragments and débris of sedimentary rocks. Frequently, however, the latter are entirely absent.

CHAPTER IV

ROCKS—*continued*

Classification of Derivative Rocks:—I. Mechanically formed Rocks, including Subaërial and Æolian, Sedimentary, and Glacial Rocks (Soil and Subsoil, Rock-rubble, Rain-wash, etc., Blown Sand and Dust, Laterite, Terra Rossa, Conglomerate, Grit and Sandstone, Greywacké, Clay, Till, etc.). II. Chemically formed Rocks—(Stalactites and Stalagmites, Tufa, Magnesian Limestone, Rock-salt, Gypsum, Siliceous Sinter, Flint, etc., Ironstones). III. Organically derived Rocks—(Limestone, Coal, etc., Guano, Coprolites).

II. DERIVATIVE ROCKS

THE rocks included under this head are of very diverse origin, and show every variety of composition, texture, and structure. Some are dominantly siliceous, calcareous, argillaceous, ferruginous, or carbonaceous; others are mixtures of many different kinds of material; while a few are composed of one mineral substance only. As regards texture, they vary from smoothly compact rocks to aggregates of the coarsest kind. So, likewise, they exhibit much variety of structure—the large majority consisting of fragmental (clastic) materials, while not a few are crystalline or subcrystalline. All derivative rocks are of *epigene* origin, *i.e.* they have been produced at or near the surface of the earth by the action of the various superficial agents of change—wind, rain, frost, water, etc. Hence many have been formed mechanically; others, again, are due to chemical action; while yet others are of organic origin. As a rule they are characterised by a more or less pronounced bedded arrangement, and hence are often termed collectively the "Stratified Rocks." Furthermore, as water has played the most important part in their formation, they are not infrequently spoken of as the "Aqueous Rocks." As some, however, show no trace of aqueous action, while certain others are not stratified or arranged in layers, we may designate the class by the more comprehensive term of **Derivative Rocks.** For, as we shall learn, all the rocks in question are composed of materials derived from the breaking-up and disintegration of pre-existing minerals and rocks by epigene agents, and from the débris of plants and animals.

Various systems of classification have been adopted for the Derivative Rocks, none of which can be said to be quite satisfactory. Perhaps as convenient a system as any is that which is based on the geological origin of the various rocks. At all events, it has the merit of directing the student's attention to the action of the various epigene agents of change which are so ceaselessly employed in modifying the crust of the globe. We shall therefore group the series under these three heads :—MECHANICALLY FORMED, CHEMICALLY FORMED, and ORGANICALLY DERIVED, Rocks.

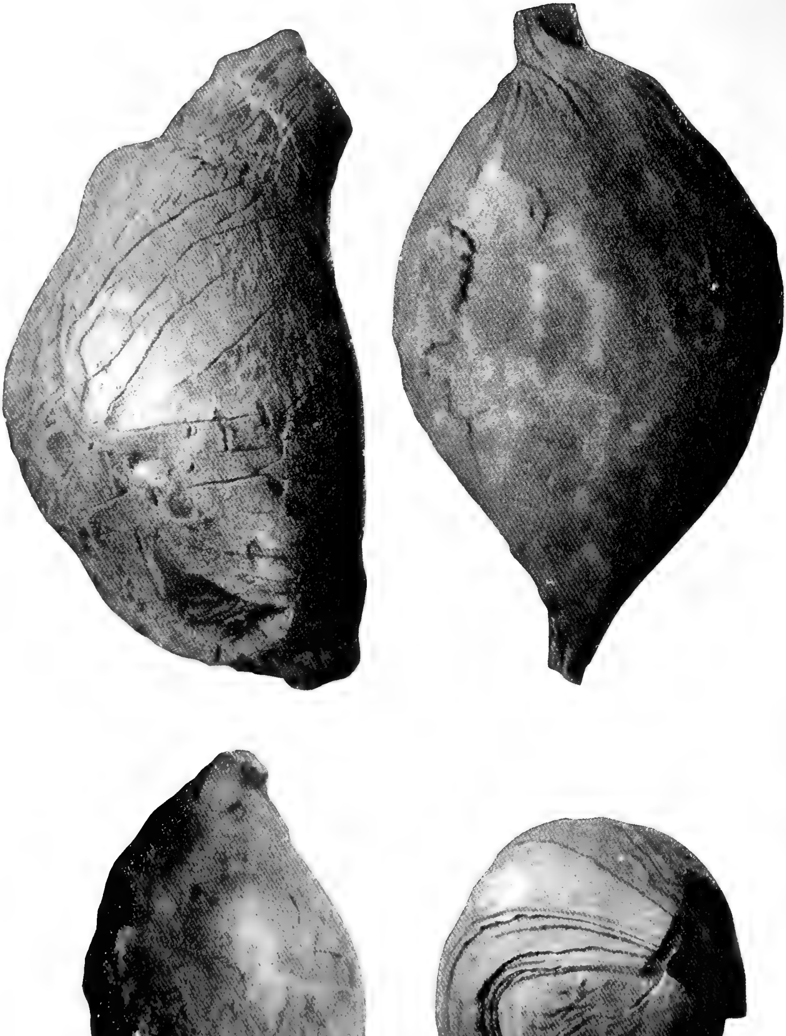
I. Mechanically formed Rocks

The vast majority of these rocks consist of fragmental materials—they are, in short, aggregates of fragments of minerals and rocks. Some of them are due to "weathering" and the action of wind; others are the products of the action of moving water; while yet others are the result of the action of ice. We have thus three types of mechanically formed derivative rocks, namely, 1. *Subaërial and Æolian Rocks*, 2. *Sedimentary Rocks*, and 3. *Glacial Rocks.*

1. SUBAËRIAL AND ÆOLIAN ROCKS

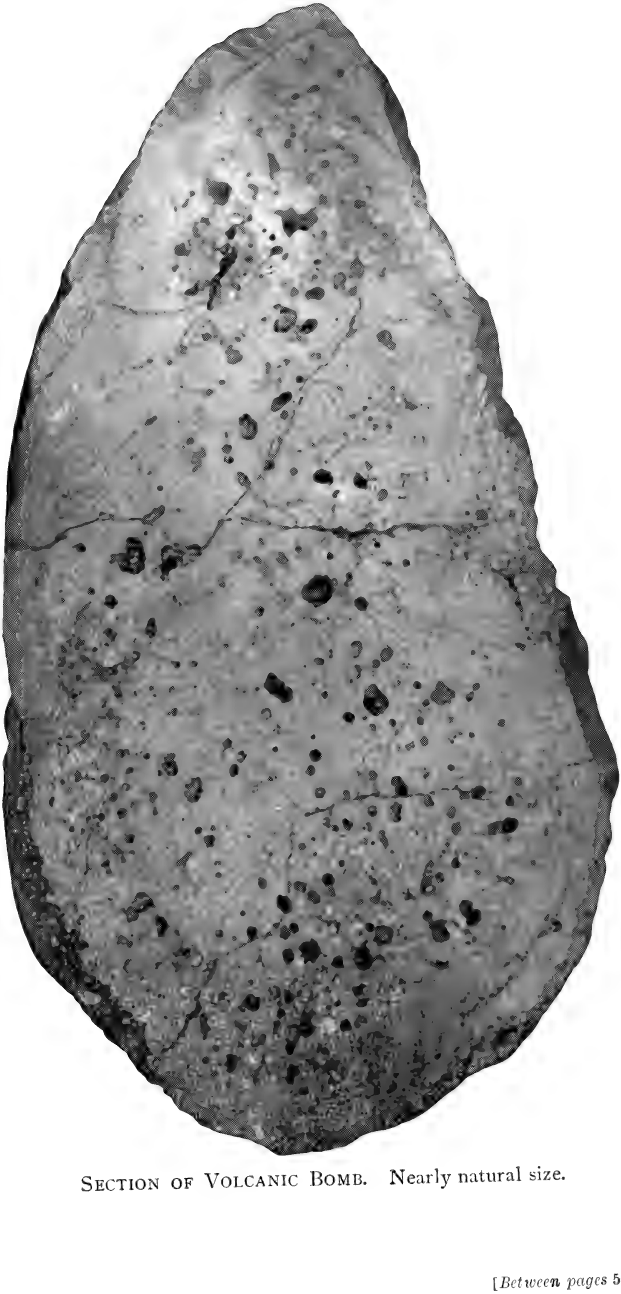
Under this head are included all accumulations which are due to "weathering" and the action of wind. The process known as "weathering" is by no means, however, exclusively mechanical. The subaërial disintegration of rocks is brought about by the operation of various agents, and it is not always possible to assign to each its proper share in the work performed. In cold regions, rocks are broken down chiefly by the action of frost; in many temperate countries the chemical action of rain is often the most effective agent of destruction, or the work of demolition may be pretty equally divided

PLATE XVII.



Volcanic Bombs. Cinder Buttes, Idaho.

From *Bull. U.S. Geol. Survey*, No. 199.



SECTION OF VOLCANIC BOMB. Nearly natural size.

[*Between pages* 56 *and* 57.

between rain and frost; while in hot and dry deserts, rocks crumble away mainly under the influence of insolation—they expand when heated up during the day, and contract more or less rapidly at night, and thus their constituent ingredients lose cohesion and the rocks become disintegrated. Some or all of these operations, it is obvious, may be carried on concurrently, almost anywhere, so that it is usual to include them under the general term of *weathering*. Of subaërial and æolian rocks, the most important are the following:—

Soil and **Subsoil.**—The particular origin of these will be fully discussed in Chapter XXIV., and they need only be shortly defined at present. *Subsoil* is an unconsolidated heterogeneous aggregate of disintegrated rock-material; while *Soil* is essentially the same, with the addition of organic matter.

Rock-rubble is the general term applied to collections of angular fragments which owe their origin chiefly to the action of frost in high northern and temperate regions, and mainly to insolation in low latitudes. Familiar examples are the taluses of stony débris which gather at the base of precipice and scaur, and the sheets of angular rock-rubbish which curtain the hill-slopes of our mountain areas. A rubble of angular fragments formed in this way, if cemented together, would be called *Scree-breccia*. [There are many kinds of breccia—this term being qualified in each case by some adjective descriptive of its origin or the character of its dominant components.]

Rain-wash, Brick-earth, etc.—In this and other temperate regions the finer grained material derived from the disintegration of rocks by weathering is gradually washed down by rain from higher to lower levels, and tends to accumulate on gentle slopes and in hollows. This rain-wash is occasionally sufficiently fine-grained and plastic to serve for brick-making purposes (*brick-earth*). But rain-wash may, on the other hand, consist of very coarse materials. In some countries where the rainfall is crowded into a short space of time, sudden torrential rains sweep the steeper declivities of the land bare of rock-débris, and spread the materials over the low-lying tracts that extend outwards from the hills and mountains. The stones included in such accumulations are more or less angular, having travelled usually no great distance.

Besides rain-wash and brick-earth there are various other products of the weathering of rocks, but these will be considered later on when we come to discuss the nature and origin of soils and subsoils.

Laterite is a red or brown, porous or cellular, ferruginous clay, common in India and other humid tropical countries. The ferruginous constituent may be diffused equally through the mass, or aggregated irregularly. Laterite is readily dug up, but becomes very hard when dried. It is the product of the subaërial decomposition of various rocks, such as gneiss, mica-schist, and other crystalline schists, diorite, basalt, and other eruptive rocks.

Terra rossa is a red or brownish ferruginous earth met with more or less abundantly in regions composed of limestone and calcareous rocks. It is simply the insoluble residue derived from the dissolution of these rocks by atmospheric action. It assumes a great development in the limestone regions of southern Europe, but may occur wherever such rocks are exposed to the action of the weather. The red earth, so frequently met with in limestone caves, is of the same origin, and has been introduced for the most part by rain and melting snow, through fissures communicating with the surface.

Blown Sand and **Dust.**—*Blown Sand* accumulates under all conditions of climate—wherever, indeed, loose sand is exposed to *deflation* or the transporting action of the wind. Hence dunes and sheets of wind-blown sand are well developed upon certain sea-coasts and lake-shores, and in the broad, flat valleys of many large rivers. In such regions, however, the wind acts chiefly as a transporter of disintegrated rock-material—the sand having already been prepared for it by the action of other superficial agents, such as tidal currents, waves, rivers, etc. In dry, desert tracts, however, blown sands owe their origin and distribution mainly to the combined action of insolation and deflation. By alternate expansion and contraction rock-surfaces are broken up and comminuted, and the grit and sand thus formed are carried forward by the wind. This loose material, swept against upstanding rocks, acts as a kind of sand-blast which abrades, frets, honeycombs, and undermines them—in other words, the sand that results from the action of insolation grinds and reduces to sand and dust the exposed rock-surfaces against which it is borne. As the travelling sand-grains, which seldom rise more than a few feet above the surface, are continually subject to mutual attrition, both in the air and upon the ground, they tend to become more or less well rounded. This character often serves to distinguish desert blown sand from sand of alluvial origin—the smaller grains of which are rather angular or subangular in shape. Having been carried mainly in suspension, they escape the constant trituration to which the grains of blown sand are subject. Blown sand, as a rule, consists principally of quartz—the commonest and one of the hardest of rock-forming minerals. In coastal tracts, however, the dunes, while consisting chiefly of quartz, often contain many other ingredients, more especially comminuted shell-débris. Further, the grains of coastal blown sand are not infrequently coarser and less well rounded than those of desert sand.

Dust is pre-eminently a product of relatively dry regions and of deserts—wherever, indeed, the land is naked or only partially clothed with vegetation, dust is formed, and may be swept up and transported by the wind. While the blown sand of a desert rises only a few feet or yards above the ground, the powdery dust is often swept upwards to a great height, and may be transported for hundreds or thousands of miles from the place of its origin. The fine-grained, homogeneous, calcareous, and sandy loam known as *Loess*, which occupies wide areas in middle and south-eastern Europe, and covers vast tracts in China, is supposed by many geologists to be essentially a dust deposit or "steppe formation."

2. SEDIMENTARY ROCKS

The rocks included under this head owe their origin to the mechanical action of water, and are usually, therefore, arranged in layers or beds. They vary exceedingly in texture—from coarse aggregates of boulders and shingle to sediments composed of the finest impalpable materials. Less sharply distinguished from each other, as a rule, than is the case with igneous rocks, sedimentary rocks of various kinds often merge into one another—coarse-grained grits and sandstones, for example, passing gradually into the finest argillaceous accumulations. The coarser-grained accumulations are almost invariably of shallow water origin—deposited at or opposite the mouths of rivers and along the sea-shore between low- and high-water levels. The medium grained masses have been laid down generally in somewhat deeper water—or in places where aqueous action was less strenuous. The finest grained sediments have accumulated in still water, and therefore usually at some distance from the land. Such being the origin of sedimentary rocks, it is not surprising that they should frequently contain the relics of animals and plants, *i.e.* fossil organic remains.

Conglomerate is a bedded or amorphous aggregate of waterworn stones, and may be either of marine or freshwater origin. It is, in short, simply a more or less consolidated gravel. The matrix in which the stones are set is usually gritty or sandy, and may be scanty or abundant. The rock often graduates into *pebbly grit* and *conglomeratic sandstone.* The cementing material may be siliceous, calcareous, argillaceous, or ferruginous. Quartz and hard siliceous rocks are usually the most conspicuous components of conglomerate. *Aqueous Breccia* is a consolidated rock-rubble, which has been accumulated in water.

Grit and **Sandstone.**—These are simply coarser and finer grained varieties of one and the same kind of rock—namely, compacted or cemented grit or sand. The most abundant component is usually quartz, but many other ingredients may be present. Amongst these may be felspar (more or less kaolinised), and occasionally some of the less readily decomposed minerals derived from the disintegration of igneous and schistose rocks, such as zircon, schorl, garnet, etc. The finer grains of an aqueous sandstone, unlike those of desert sand, are often angular or subangular, while the larger grains and small pebbles are usually well waterworn and rounded. Sandstones may be white, grey, yellow, brown, red, greenish, or black. The colouring matter is in most cases due to that of the cementing or binding material, which may either be dispersed between the grains, as in carbonaceous sandstones, or appear as thin pellicles or skins enveloping the individual particles. White and light grey sandstones and grits usually have a calcareous or a siliceous binding material, or they may have been compacted by pressure alone. Yellowish and brownish colours are due, for the most part, to ferric hydrate, and red colours to hæmatite (ferric oxide), while greenish hues frequently indicate the presence of some impure hydrous silicate of iron and other bases.

Varieties :—*Freestone* or *Liver-rock*, a fine-grained homogeneous sandstone capable of being tooled equally well in any direction. *Flagstone*, a thin-bedded, fine-grained sandstone, which separates readily along the bedding-planes, frequently more or less argillaceous, and often micaceous. *Micaceous sandstone*, fissile, usually fine-grained, with abundant scales of white mica. *Greensand*, a sandstone of a dull greenish colour, owing to the presence of disseminated glauconite. *Grit*, simply a coarse-grained sandstone. *Arkose*, a sandstone composed of quartz, felspar, and mica ; derived directly from the disintegration of granite or gneiss.

Greywacké is a more or less indurated rock, composed of rounded, subangular, and often sharply angular grains of quartz, felspar, hornstone, slate, and other minerals and rocks, amongst which scales of mica are not infrequently conspicuous. Besides such grains, greywacké usually contains in less or greater abundance flakes and splinters of various compact rocks, such as slate, hornfels, lydian-stone, felsite, etc. The cementing material is usually meagre and often siliceous, but it may be argillaceous, calcareous, or ferruginous, or even anthracitic. Grey and blue are the commonest colours of the rock, but green, brown, red, purple, yellow, and even black varieties occur. The texture varies from compact and fine-grained to coarse-grained and brecciiform. The rock occurs in thin layers and massive beds, interstratified with slaty shales and slates, and is practically confined to the older geological systems (Palæozoic).

Clays.—These are aggregates of very finely divided mineral matter, which become plastic when moistened. The finer varieties appear to the unassisted eye quite homogeneous, and when squeezed between the fingers have an unctuous feel, and seem as if composed of some impalpable substance. With the exception of kaolin, however, clays are really heterogeneous aggregates of various minerals and different kinds of rock material.

Two distinct varieties of common clay are recognised—namely, *alluvial clay* and *glacio-aqueous clay*. In *alluvial clay* the finer grained constituents are obviously the result of the chemical decomposition of minerals and rocks, and consist largely of hydrous silicate of alumina. Disseminated through this material occur minute grains of quartz, and frequently fine flakes of pale or colourless hydrous mica. Other constituents present in ever-varying proportions are iron-oxides and carbonates of calcium, magnesium, and potassium. Clays of this character are invariably of secondary origin ; they have been derived from the disintegration and decomposition of rocks, partly a mechanical but largely a chemical process. They consist, in short, chiefly of the insoluble residue of rocks. *Glacio-aqueous clay*, on the other hand, owes its origin mainly to the mechanical grinding and pulverising of rocks by glacier-ice, and consists therefore chiefly of fine rock-flour or rock-meal, reassorted and deposited in water without having undergone much chemical alteration. When clays of this character are microscopically examined, we find not only abundant grains of quartz and flakes of relatively fresh mica, but particles of many other minerals, such as various felspars and other silicates, all more or less fresh and chemically unaltered. The proportion of hydrous aluminium-silicate present is much less than in the case of clays of alluvial origin. It is generally assumed that the hydrous aluminium-silicate in clays of all kinds is kaolin, but this has not yet been demonstrated. The common belief that the plasticity of clays is due to the presence of the hydrous silicate in question is even more doubtful. Almost any rock-forming silicate—nay, quartz itself, if reduced by grinding and rubbing to the consistency of an impalpable powder—becomes plastic when moistened, and has the earthy odour of clay.

Varieties of Clay.—*Kaolin* is a product of the decomposition of highly felspathic rocks (granite, gneiss, etc.). The purer kinds of kaolin occur *in situ*—*i.e.* they occupy the site of the altered rock, and probably owe their origin to the action of heated solutions and vapours coming from below. When kaolin has been washed away from its place of origin and deposited elsewhere it is never so pure as that which has not travelled, but is often mixed with many other ingredients. The purest kaolin is a silvery white powder, consisting entirely of very minute six-sided plates of the mineral kaolinite—a hydrous silicate of alumina with a definite chemical formula ($H_4Al_2Si_2O_9$). When moistened, this aggregate of scaly kaolin, or *Kaolinite*, is plastic. The *Kaolin* or *China-clay* of commerce, however, usually contains many impurities ; it is rather a rock than a mineral. *Pipeclay* is a fine white clay which shrinks too much on the application of heat to be available for pottery-making. It contains a larger percentage of siliceous matter than kaolin. *Fire-clay* is a clay containing little or no lime, alkaline earths, or iron, which act as fluxes. It is thus infusible or highly refractory and suitable for bricks, etc., which are required to stand intense heat. *Brick-clay* is an intimate admixture of clay and sand with some iron-oxide, and is used for ordinary bricks. *Fuller's earth* is a soft, dirty greenish, brownish, blue, yellow, or grey variety of clay, somewhat greasy or unctuous to the feel, which falls into powder in water. *Shale* is the name given to any argillaceous rock that divides into thin layers or laminæ, corresponding to planes of deposition. Shales vary greatly in composition, some containing much sand (*arenaceous shale*), others being largely carbonaceous (*carbonaceous shale*), or saturated with bituminous matter (*oil shale*). *Alum shale* is an argillaceous rock charged with a considerable quantity of disseminated pyrite or marcasite (sulphides of iron), through the decomposition of which alum (sulphate of alumina) and copperas or iron vitriol (hydrous sulphate of iron) are formed.

Loam is a mixture of sand and clay, usually containing some calcium-carbonate, the sand being plentiful enough to allow the percolation of water through the mass. Most loams are of alluvial origin, and are, therefore, commonly developed in valley-bottoms.

3. GLACIAL ROCKS

These rocks are the result of the mechanical action of ice. *Rock-rubble*, already described as a subaërial formation, might perhaps be classed as a glacial rock, since it owes its origin chiefly to the action of frost. It is preferable, however, to include here only those formations which are the products of glacial erosion and transport. Amongst these, by far the most important is **Boulder-clay** or **Till**, a more or less tenaceous, gritty clay, crowded with angular and subangular stones and boulders. It varies, however, very much in character, being occasionally more aranaceous than argillaceous. When the larger stones are removed it is often used for brick-making; in many places, however, it is too stony for such a purpose.

When subjected to mechanical analysis, the plastic materials of the till of the Scottish lowlands is seen to be a heterogeneous aggregate of minutely triturated mineral matter, and much rock-flour of a very fine consistency. Only a meagre proportion of this so-called "clay" consists of hydrous silicate of alumina, or pure clay. Boulder-clay, in short, is composed for the most part of unweathered rock-material—it is the result of glacial grinding, and has not, like ordinary alluvial clay, been formed by the chemical decomposition of minerals and rocks.

The only other glacial accumulation that need be referred to are the mounds and sheets of earthy rock-débris and boulders which occur in and opposite the mouths of many of our mountain valleys. These have been transported by the glaciers of the Ice Age as superficial *moraines*, some of the more conspicuous heaps having been dumped down as terminal moraines during long pauses in the final retreat of the old ice-flows, while hummocky sheets of the same materials were gradually spread over the flanks and bottoms of our mountain valleys as the glaciers melted more or less rapidly away.

II. Chemically-formed Rocks

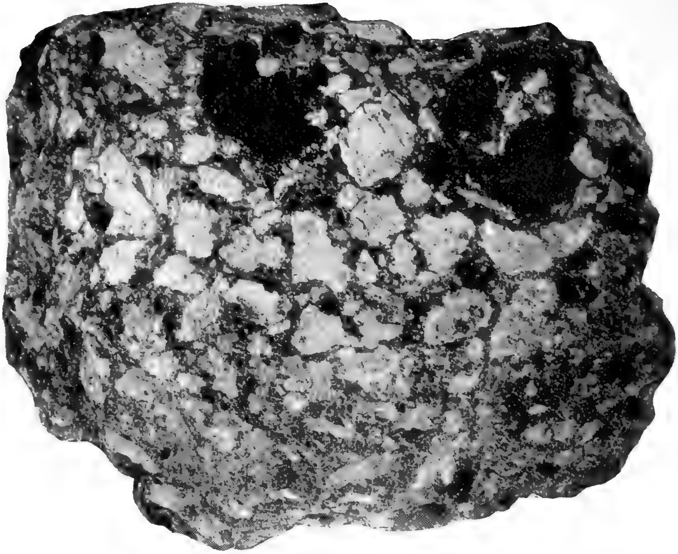
These are for the most part chemical precipitates from aqueous solutions, and are chiefly calcareous, siliceous, ferruginous, and saline. Some have been deposited at the surface as the result of evaporation; others are precipitates from saturated solutions, and have thus accumulated on the floors of salt-lakes and seas. Again, a few are of the nature of aggregations: originally diffused through the rocks in which they occur, they have since drawn together and become concentrated so as to form nodules and nodular masses or independent layers.

Stalactites and **Stalagmites.**—These are precipitates from water holding calcium carbonate in solution. They are of common occurrence in limestone caverns, the stalactites growing downwards from the roof and the stalagmites gradually accreting on the floor. Carbonated water percolating through the limestone oozes out on the roof of a cavern, and, being there exposed to evaporation, is compelled to part with some of its calcium carbonate, which adheres to the rock-surface. When the gathering drop of water falls to the ground it is there again exposed to evaporation, and gives up the remainder of the carbonate which it held in solution. The colour of these deposits varies indefinitely—they may be creamy-white, yellowish, brownish, or reddish, and are often mottled. They usually show a concentric, laminated structure, and the stalactites, in the early period of growth, are porous and readily crushed; subsequently, however, their pores become filled up with calcium carbonate, and the structure thus gradually solidifies. Stalagmites are seldom or never so porous, but exhibit a well-defined laminated structure (see Plate XIX.). In course of time both stalactites and stalagmites, owing to molecular changes, tend to acquire a crystalline structure.

PLATE XIX.

Stalagmite, Gibraltar. Nearly natural size.

[To face page 64.



1. Volcanic Tuff. Two-thirds natural size.

2. Shelly Limestone. Nearly natural size.

[*To face page* 65.

Tufa or **Calc-sinter** is formed by deposition from calcareous springs. It is a porous and frequently very friable compound of calcium carbonate. The colour varies; creamy-white and yellow tints are common, but red and brown are not infrequent, while some kinds are greenish or bluish. The rock is often mottled or marked with concentric bands of different colours. *Travertine* is the name given to hard and compact varieties used for building-stones. They have frequently a crystalline or subcrystalline structure. Some tufas and travertines consist largely of small spherules of calcium carbonate, composed of concentric layers which have been deposited successively around some nucleus, such as a particle of sand or a minute fragment of calcareous matter. When the spherules are small, resembling fish-roe, the rock is termed *Oölite;* when they are of the size of peas the rock is known as *Pisolite.*

Dolomite or **Magnesian Limestone** is a crystalline granular or earthy aggregate of the mineral dolomite or bitter-spar (double calcium and magnesium carbonate). It effervesces only slightly with cold dilute hydrochloric acid, but is readily attacked when the acid is heated. Ferrous carbonate and various impurities are more or less commonly present. When such is the case the rock is usually yellowish; when impurities are only sparingly present it is grey or white. It frequently assumes a concretionary structure, showing botryoidal and irregular shaped masses, or appearing as if built up of spherical bodies that may vary in size from small marbles up to large cannon-balls. Lines of bedding pass through these curious concretions. Many irregular shaped cavities appear in dolomite, and these are often lined with crystals of bitter-spar. Typical dolomite is easily distinguished from ordinary limestone by its superior hardness (3·5 to 4·5), its greater specific gravity (2·8 to 2·9), and its much less ready solubility in cold acid.

Some dolomites, especially those which are associated with beds and layers of rock-salt and gypsum, may be of the nature of chemical precipitates on the floors of salt-lakes, lagoons, and other bodies of highly saline water. Many, however, would appear to have been originally common limestones which, either at the time of their formation or subsequently, have by various chemical processes been converted into magnesian limestones. Few limestones are without some proportion of magnesia, so that it is not possible to draw a hard-and-fast line between common limestone and magnesian limestone. It is only when the magnesia forms 20 per cent. or so of the rock that the latter is included among the dolomites or magnesian limestones—but between this and limestones which contain little or no magnesia, there are all gradations.

Rock-salt is a crystalline, fibrous, or even granular aggregate of sodium chloride, which occurs either in thin layers or in massive beds, sometimes reaching a thickness of several hundred feet. When pure it is clear and colourless, but is often stained with impurities, being frequently red, yellow, or grey. Blue and green tints also occur, but they are not common. The mineral is frequently turbid owing to admixture with sandy or argillaceous matter. In many places, indeed, it passes into a saliferous clay. It is usually associated with gypsum, anhydrite, and dolomite, interstratified with clay, marl, and red or particoloured sandstones, and has obviously been deposited in salt lakes or in arms of the sea more or less cut off from the general body of open water.

Gypsum, hydrous calcium-sulphate, occurs in beds, layers, or lenticular sheets and masses, and is often associated with rock-salt, anhydrite (calcium sulphate), dolomite, red clay, and sandstone, etc. In structure it varies from compact to granular, or it may be a fibrous, scaly, or sparry aggregate. When relatively pure it is white or quite colourless, but is often stained yellow or red by iron-oxides, or coloured grey and brown, owing to admixture with clay or other impurities. The exceedingly fine-grained varieties are known as *Alabaster*. Compact gypsum is readily distinguished from limestone, which it sometimes resembles, for it is scratched by the finger nail, while limestone is not.

Siliceous Sinter is an aggregate of amorphous silica containing a variable proportion of water. It may be loose, unconsolidated, and porous, or dense and compact, and often assumes stalactitic and stalagmitic forms. When free from impurities it is white, but as these are often present it may be stained various shades of yellow or red. It is formed by deposition from thermal springs, as the result of evaporation; in some cases, however, deposition is partly due to the action of minute algæ, which occasionally flourish in the hot pools of a geyser region.

Flint is a hard grey or black rock, composed of amorphous or chalcedonic quartz—the dark colour being due to carbonaceous matter. It breaks with a marked conchoidal fracture, and is translucent along the sharp cutting edges. Its most characteristic occurrence is in the form of nodules, layers, and vertical ramifying or vein-like masses in white chalk.

Its precise mode of formation is not quite clear, but it would appear to be partly of organic, partly of chemical, origin. Sponges and other organisms secrete soluble silica from sea-water, and when they die additional silica is deposited upon and within their skeletons and exuviæ. Calcareous shells, and even the chalk itself in which these are embedded, have often been partially or wholly replaced by silica, so that silica in a soluble form must have been diffused to some extent through the calcareous ooze of Cretaceous seas. Probably the silica was largely derived from the skeletal remains of sponges, which flourished in great abundance during the formation of the Chalk. *Chert* is a somewhat impure kind of flint, of not uncommon occurrence in limestones belonging to the older geological systems (Palæozoic), and, like it, probably partly of organic, partly of chemical, origin. In some cases, however, it possibly represents the deposits of thermal springs. *Hornstone* is a somewhat similar rock; it is more brittle than flint. *Lydian-stone* is a mixture of silica and clay, usually with carbonaceous or ferruginous matter. It is black, purplish, red, or dark blue, very hard and compact, and often much cracked and rent, the small fissures being usually filled with white quartz. It occurs in thin beds and layers in the older Palæozoic systems, and in some cases, at least, contains remains of radiolarians (*Radiolarian Chert*), so that such rocks would appear to represent the radiolarian ooze of ancient seas.

Ironstones are sometimes of chemical, sometimes of organic, origin, or partly both. Occasionally they occur in the form of beds or layers interstratified with other derivative rocks, or of nodules and nodular masses embedded chiefly in argillaceous deposits. They are frequently met with also occupying fissures and irregular cavities. *Limonite*, when approximately pure, is a compact fibrous or stalactitic aggregate, in which form it usually occurs in veins and cavities. When appearing as a bedded rock, it is usually earthy and porous, and crowded with impurities. It forms the hardpan which so frequently appears under marshy ground (*Bog Iron-ore*), and often occurs as a lacustrine formation in layers of small spherical bodies (*Oölitic* or *Pea Iron-ore*). *Hæmatite*, already described as a mineral, appears as rock-like masses in beds, veins, and cavities (especially in limestones). Not infrequently it is found replacing limestone (see under ORE-FORMATIONS). As a rock it usually contains many impurities, such as clay, quartz, oxide of manganese, etc. It passes into ferruginous clay, etc. *Spathic Iron-ore* is a granular or compact aggregate of siderite, occurring in beds and as veins, especially among the older geological systems. *Clay-ironstone* is a variety of spathic iron-ore, containing much clay. It is brown to dark grey or black, and appears as thin beds and layers, or in the form of balls and nodules. It is a very common rock among the argillaceous strata of the Carboniferous system. In some cases it appears to have been deposited on the floors of ancient lakes, lagoons, and estuaries; in other cases it is of a concretionary nature — the ferruginous matter originally diffused through an argillaceous bed having become aggregated around fossils or other foreign bodies, so as to form nodules of various size. Many of these nodules are septarian (Plate XXVII.). *Blackband-ironstone* is simply a clay-ironstone, containing a large proportion of carbonaceous matter (from 10 to 52 per cent.). *Magnetic Iron-ore* sometimes occurs in beds amongst fossiliferous strata, in which case it has resulted from the alteration of limonitic ore. Magnetic iron-sands are often met with in regions where certain igneous rocks abound, from the disintegration of which the magnetite has been derived. (For other occurrences of magnetic iron-ore, see under ORE-FORMATIONS.)

III. Organically derived Rocks

The more important rocks included in this division are largely composed of organic remains—plant or animal as the case may be. Some, however, are due, or partly due, rather to the action of living organisms. Amongst the latter are Flint and some kinds of Calcareous Tufa and Ironstone. The origin of flint has already been briefly considered (p. 67). Bog iron-ore not infrequently owes its origin to the action of the minute plants known as diatoms, which are able to separate iron from water, and to deposit it about and within their substance as a hydrate. Water-loving plants are also largely concerned in the formation of calcareous tufa, which is not always due entirely to the mere evaporation of aqueous solutions. The carbonic acid which enables the water to hold the calcium-carbonate in solution is decomposed by bog-mosses and their allies, and a calcareous crust is thus gradually deposited upon the plants. Many thick masses of tufa have in this way resulted partly from chemical, and partly from organic action. Considerable accumulations of siliceous sinter are likewise due in large measure, as already indicated, to the vital action of minute algæ. But of still greater importance are the rocks which owe their formation to the action of humus acids derived from the decomposition of organic matter. These acids attack the iron-bearing mineral constituents of rocks, and form ferruginous solutions; and when such solutions are exposed to the air, they are oxidised, and hydrate of iron (bog iron-ore) is precipitated. There can also be little doubt that organic acids, derived from the decomposition of sponges and other forms of life, have had much to do with the formation of flint and chert, which might, therefore, be included among organically derived rocks as fitly as under chemically formed rocks. The most characteristic representatives of the former class, however, are the calcareous and carbonaceous rocks, of which there are many varieties.

Limestone.—Of this rock there are innumerable kinds. All are composed essentially of carbonate of lime, but few do not also contain carbonate of magnesia. While some are very pure, others are crowded with impurities. They vary greatly also as regards texture—ranging from extremely fine-grained and compact rocks to coarse aggregates of shells and corals. Grey and greyish-blue are the commonest colours, but there are many others, such as green, purple, yellow, red, grey, black, and pure white. While limestones differ as regards their hardness and specific gravity, the common and most characteristic types have usually a hardness of 3 or thereabout, and a specific gravity of 2·6 to 2·8. One of the best known limestones is common *Chalk*—a white fine-grained earthy rock, generally soft and meagre to the touch, soiling the fingers. It is largely composed of the shells of foraminifera, together with the débris of various forms of marine life—more or less reduced to the condition of a fine meal or flour. *Oölite* is similarly composed of organic débris, but is characterised by the oölitic structure already described as occurring in certain chemically formed calcareous deposits. In thin sections seen under the microscope the spherules show a concentric and radiated structure—the latter, however, being sometimes wanting. Similar spherules have been observed forming not only in mineral springs such as those of Carlsbad (*Sprudelstein*), but in shallow water in the Great Salt Lake of Utah, and on the coral beaches of the Bahamas. They obviously owe their origin to deposition of calcareous matter on particles of sand which are kept in motion so as to become more or less equally encrusted. *Shell-marl* is an earthy aggregate of shells (most frequently of freshwater origin), with a larger or smaller proportion of argillaceous matter. It often passes into *Lacustrine Limestone*, which is usually a fine-grained, dull white or grey rock—sometimes earthy, sometimes compact.

Limestones, which are composed conspicuously of the débris of crinoids, corals, or shells, as the more prominent ingredients of the rock, are known respectively as *Crinoidal*, *Coral*, and *Shelly* limestones (see Plate XX. 2). Occasionally, the organic structure of such rocks has been obscured or even entirely effaced by subsequent molecular changes—the mass becoming crystalline. Shelly limestones often acquire special names, according to the relative abundance of some particular shell, as *Nummulite-*, *Hippurite-*, *Ammonite-*, *Gryphæa-limestone*, etc. *Common Limestone* is usually grey or blue, and fine-grained to compact. In many common limestones the organic structure is only revealed in thin sections under the microscope. On the weathered faces of such rocks, however, fossil remains may often be readily detected. There are many varieties of common limestone characterised by the presence of certain impurities and admixtures. Amongst these may be mentioned *Cornstone*, a highly calcareous sandstone or arenaceous limestone, sufficiently rich in calcium carbonate to be burnt for lime, when a better rock is not available. *Cement-stone* is a dull argillaceous and sometimes ferruginous limestone, often occurring in thin beds and layers in the same way as clay-ironstone. It is sometimes used for making hydraulic cement. *Carbonaceous Limestone* contains a considerable quantity of carbonaceous matter; limestones of this kind often emit a fetid odour when rubbed or struck with a hammer. *Rotten-stone* is a siliceous limestone, from which calcium-carbonate has been removed in solution, so as to leave only the skeleton of the rock.

Carbonaceous Rocks.—Under this division are grouped all accumulations of vegetable débris and the products of their destructive distillation by natural causes. The least mineralised accumulations are included under the head of *Peat* or *Turf.* This might be described as a yellow, brown, or black aggregate of vegetable débris, interwoven, as it were, and more or less compressed and decomposed. Impurities are common, such as various earthy admixtures, ochre, limonite, pyrite, diatomaceous remains, etc., and the amount of ash after combustion is very variable. *Lignite* or *Brown Coal* is a compact or earthy mass, brown or black with a brown streak, and very inflammable. It differs from common coal in containing a greater proportion of bitumen, or the elements which combine with carbon to form bitumen. The proportion of carbon in lignite ranges from 55 to 75 per cent. *Common Coal* is a black, compact carbonaceous mass, which on a fresh fracture has usually a resinous lustre. It has a black streak; is commonly friable; is not so inflammable as lignite; and contains 75 to 85 per cent. of carbon. The percentage of oxygen, hydrogen, and nitrogen (the elements which with carbon form bitumen), is lower than in lignite, but higher than in anthracite.

Varieties of Common Coal.—These probably owe their distinctive characters to the nature of the plants or portions of plants of which they are composed. The chief kinds are Caking-coal, Cherry-coal, Splint- (Hard-, or Steam-) coal, and Cannel-coal. *Caking-coal* has a short, uneven fracture, while *Cherry-coal* breaks with a clear shaly fracture: the former fuses or runs together when burnt, the latter does not. These are the so-called "bituminous coals." *Splint-coal* has a cubical fracture, is not so shattery or friable as the bituminous coals, and is more difficult to ignite than these, but has greater heating-power. *Cannel-coal* is smoothly compact, breaks with a conchoidal fracture, does not soil the fingers, burns with a clear flame like a candle, and crackles or chatters when burnt—hence the common name *Parrot-coal.* *Anthracite* (*Stone-* or *Blind-coal*) is the most highly mineralised form of coal, consisting almost entirely of carbon. It is black with a vitreous to submetallic lustre and a black streak ; is not easily ignited, and burns almost without smoke or smell. Now and again coal (of Carboniferous age) has been converted into *Graphite* (approximately pure carbon), owing to the action of intrusive igneous rocks. In such cases it has been subjected to a kind of destructive distillation, all its gaseous elements having been eliminated. Graphite also occurs in lenticular layers amongst crystalline schists, but its precise origin in such conditions is uncertain. *Oil-shale* (Bituminous schist) is a dark brown or black highly bituminous shale, which is readily ignited, but cannot of itself be used as a fuel, owing to its containing so much argillaceous matter. *Asphalt*, an admixture of various hydrocarbons, is probably in most cases the result of the distillation of coals or other organic matter by intrusive igneous masses. It is solid or highly viscous at ordinary temperatures ; black or brownish-black, with a pitchy lustre and a bituminous odour. It occurs in sheets or layers interstratified with sedimentary rocks, or as impregnations in such rocks as limestone and sandstone, or occupying fissures and cavities in the same. Not infrequently it is met with in veins traversing rocks of various kinds and age, and in certain regions it exudes from the ground, forming what are known as "tar-springs." *Petroleum* is a general name for complex hydrocarbons, which are liquid at ordinary temperatures, but vary greatly in this respect, some of them being more or less viscous. They occur mainly in rocks of a porous character. The origin and source of the petroleum or rock-oil derived from the Palæozoic rocks of North America is at present unknown.

Guano is an earthy, white, grey, or yellowish-brown accumulation, with a peculiar odour. It consists mainly of the excrement of birds, mixed with the offal and débris of their repasts, and not infrequently with their own remains, together with those of seals, etc. It contains some 40 to 50 per cent. of organic matter and ammonia salts, with 19 to 20 per cent. or thereabout of phosphate of lime. Immense deposits of it have been met with in the rocky islets lying off the west coast of South America (Peru) and Africa, but these are now largely exhausted.

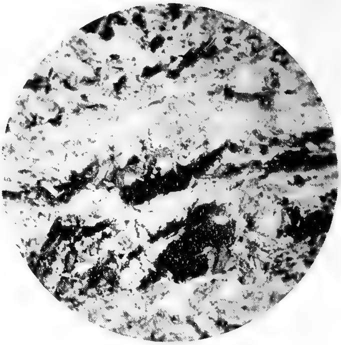
Leached Guano.—Guanos long exposed to the action of rain tend to have the soluble nitrogenous constituents dissolved out, so that the relatively non-soluble phosphatic ingredients become in this way concentrated. Some of the phosphoric acid (in the form of ammonia-phosphate) is carried down into the underlying rock, which becomes phosphatised. Limestones, when these are present, thus tend to become converted into tribasic phosphate of lime.

Rock-guano is a deposit from which all the soluble nitrogenous products have been leached out, so that only calcium-phosphate remains.

PLATE XXI.

MICROSCOPIC STRUCTURE OF SCHISTOSE ROCKS.

1.

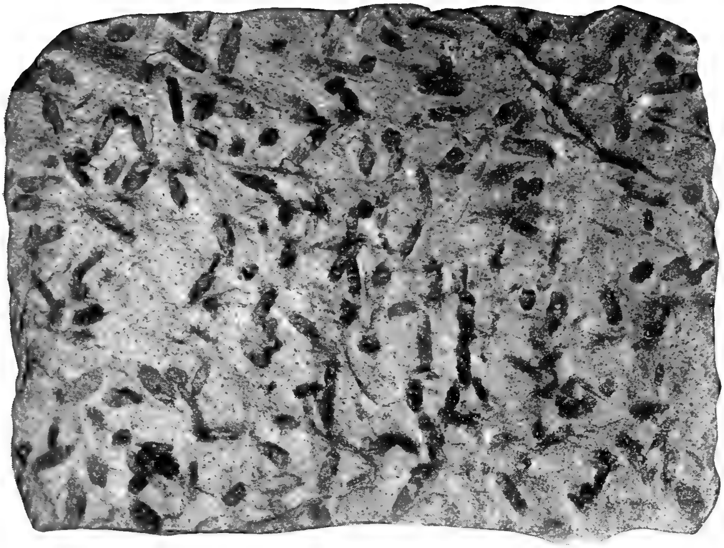


2.

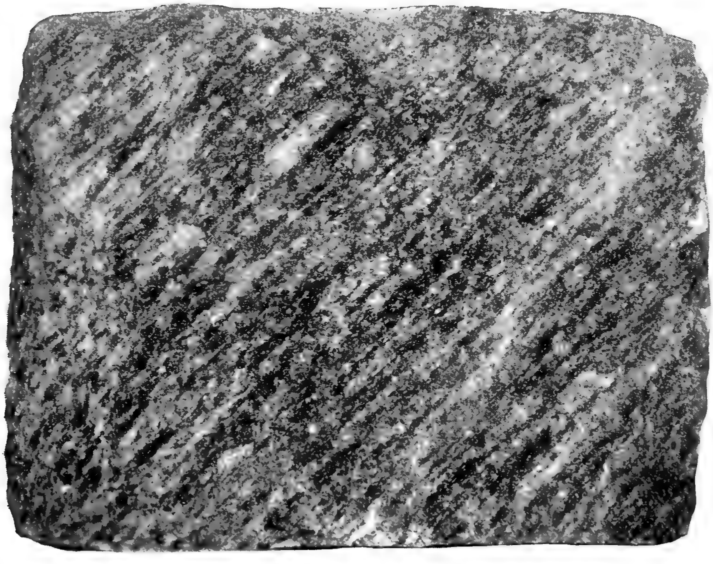
3.

1 and 2. Foliated Structure of Biotite Gneiss.

3. Schistose Conglomerate. Nearly natural size. (From Lehmann's *Entstehung der altkrystallinischen Schiefergesteine.*)



1. Spotted Slate. Nearly natural size.



2. Gneiss. About two-thirds natural size.

[*Between pages* 72 *and* 73.

This substance is known in commerce as "rock-guano," "rock-phosphate," etc.

Coprolites are the droppings of fishes, reptiles, or mammals, in a more or less fossilised condition. They are met with in strata of widely different age, but the coprolites of commerce are usually phosphatic nodules, often of a concretionary nature, and not fossil excrements. Phosphatic nodules of this kind sometimes occur in regular beds, as in the Upper Greensand and at the base both of the Red and the Coralline Crags of England. They are similarly very abundantly developed in the neighbourhood of Charlestown, South Carolina.

The origin of these nodules is quite uncertain. They often contain fossils, and in some cases are obviously portions of the rock underlying the bed in which they occur. In short, they are fragments of some calcareous rock, such as Chalk, which have been rolled and rounded, and in some way or other have become impregnated with phosphoric acid. As this acid may have been derived from marine plants, it has been suggested that the nodules may have become phosphatised during the long-continued growth and decay of sea-weeds. In many cases, however, the nodules are certainly of a concretionary nature, and often contain no fossils. They are frequently very hard, and may possibly represent the residuum of ancient guano-beds—that is, the relatively insoluble constituents of such organic accumulations, which have been washed down from some neighbouring land. Yet another source of such concretions has been suggested. It is known that a small percentage of phosphate of lime of organic origin is invariably present in the marine organic oozes which have been dredged from great depths, and it has been detected also amongst the fine-grained sands and muds which are being accumulated around continental shores. It is supposed, therefore, that calcareous deposits, such as the phosphatic chalk of this and other countries, may have derived their phosphoric acid from a similar source, and that the so-called coprolites are simply concretions formed in the usual way by aggregation of diffused mineral matter.

CHAPTER V

ROCKS—*continued*

Metamorphic Rocks—*A.* Schistose Rocks, their General Characters. Quartzose Rocks. Argillaceous Rocks. Mica-schist. Gneiss. Chlorite-schist. Talc-schist. Amphibolites. Granulite. Marble. Serpentine. *B.* Cataclastic Rocks, their General Characters. Mylonites, Friction-breccias. Determination of Rocks in the Field. General Characters of Argillaceous, Calcareous, Siliceous, and Felspathic Rocks. Specific Gravity of Rocks.

III. METAMORPHIC ROCKS

A. Schistose Rocks

THE rocks of this great class are for the most part crystalline, and characterised by the structure known as *foliation.* In a foliated rock or *schist* the constituent minerals, which may consist of one or of several species, are arranged in more or less parallel layers. Each layer may be composed of one kind of mineral only, or two or more different kinds may be commingled. The layers or folia are usually lenticular in form—in some cases being remarkably even and parallel, so as to give the rock an appearance as of fine lamination (see Plate XXII. 2). In other cases the individual folia thicken- and thin-out rapidly (see Plate XXIII.), alternate irregularly, are often undulating, and frequently crumpled and puckered. The several folia are not as a rule readily separated from each other—the minerals of one being usually more or less closely intermingled, felted, and welded with those of adjacent layers (see Plate XXI. 1, 2). In all these respects the foliation of a schistose rock differs markedly from the lamination of sedimentary derivative rocks. It must also be distinguished from the fluxion or fluidal structure which is so frequently present in crystalline igneous rocks.

Metamorphic rocks differ much as regards texture and structure. They are not all equally crystalline and foliated. Some, indeed, show only faint traces either of crystalline or schistose structure; others, again, although markedly crystalline, are not foliated. But no foliated rock is devoid of crystalline texture. There can be no doubt that many schists originally existed as mechanical sediments, and that their present constitution is the result of subsequent changes. This is proved by the simple fact that all gradations can be traced from unaltered sedimentary rocks into rocks which become more and more markedly crystalline and foliated as they are followed in some particular direction. Again, characteristic clastic rocks, such as conglomerate, are not infrequently met with intercalated between beds of mica-schist or other foliated rock—an arrangement obviously suggestive of the original sedimentary character of the latter. Further, the occasional occurrence of fossils in crystalline schists leaves no room to doubt that such schists are simply more or less altered or metamorphosed sedimentary rocks.

In other cases, however, it can be proved that certain foliated rocks are not originally of sedimentary origin. Again and again we encounter massive igneous crystalline rocks, such as granite, diorite, gabbro, etc., passing outwards by insensible gradations into well-marked foliated rocks. In such cases we are compelled to conclude that the foliated structure has been superinduced. In short, all truly schistose masses are metamorphic, and originally existed either as igneous or as derivative rocks.*

Quartzose Rocks.—Amongst these are included several rocks, the clastic structure and sedimentary character of which are more or less conspicuous. *Schistose Conglomerate* † is an aggregate of waterworn stones in a crystalline schistose

---

* It must be noted, however, that a mass of granite sometimes exhibits along its margin a kind of fluxion foliation which is original, and not the result of metamorphism. See Chapter XIII.

† The stones of such conglomerates are often distorted. They may be crushed and drawn out into mere lenticles along the planes of foliation, as shown in Plate XXI. 3.

matrix (Plate XXI. 3). *Quartzite* is composed of grains of quartz cemented by silica to form a very hard finely granular or compact rock. It occasionally shows traces of false-bedding and diagonal lamination, and is obviously an altered sandstone. The fracture is usually splintery, but in very compact varieties tends to be conchoidal. The rock may be white, grey, yellowish, or reddish, and even occasionally bluish or greenish. It occurs in thin and massive beds intercalated among crystalline schists.* *Quartz-schist* is a quartzite, in which a foliated structure has been developed—the planes of foliation being glazed over with scales of white mica.

Argillaceous Rocks.—The best known members of this group are the clay-slates. *Clay-slate* is a finely granular or compact clay-rock. It divides into thin plates which sometimes coincide with the original planes of deposition, but usually cross these at various angles. The colour of the rock may be blue, green, grey, purple, brown, or red. Slate is composed mainly of argillaceous matter (silicates and hydrous silicates of alumina), but many other ingredients may be present, such as quartz, mica, felspar, chloritic and carbonaceous matter, rutile, iron-oxides, pyrite, etc. Some of these minerals are original constituents of the clay, others have been developed in the rock subsequent to its formation as a sediment. The scales of mica and crystals of rutile, for example, have obviously been developed along the superinduced planes of cleavage. In some slates well-marked conspicuous crystals (chiastolite, andalusite), are disseminated irregularly, and are clearly of secondary origin—the minute fragmental particles of the slate having been pushed aside during the gradual growth of the crystals.

There are many varieties of clay-slate, such as *Roofing-slate*, with smooth cleavage ; *Pencil-slate*, a soft slate of pure composition used for writing on slate ; *Whet-slate* or *Novaculite*, a highly siliceous slate, with indistinct cleavage, used for sharpening knives ; *Anthracite-slate* and *Alum-slate*, carbonaceous slates which often contain marcasite and pyrite—the decomposition of which gives rise to the formation of alum ; *Knotted-* or *Spotted-slate* (see Plate XXII. 1), a slate containing little

---

* Now and again, however, sandstone and unconsolidated sand of relatively recent age have been partially converted into quartzite by the infiltration of silica in solution.

spots or concretionary knots which in some cases seem to be incipient stages in the development of such minerals as andalusite and cordierite; *Andalusite-*, *Chiastolite-slates*, slates marked by the presence of these minerals in less or greater abundance. Spotted slates and andalusite-slates, etc., may be little altered otherwise, or they may contain much mica, and so gradually pass into andalusite-mica-schist. *Phyllite* is more crystalline than clay-slate. It is a schistose clay-rock, the cleavage-planes of which are lustrous with white mica, and frequently finely wrinkled. It is a passage-rock between clay-slate and mica-schist. Many of the hard rocks included under the term *Hornfels* are metamorphosed argillaceous rocks. [Some, however, are altered igneous rocks, while others appear to have been originally impure limestones or dolomites (*calc-silicate hornfels*).]

Mica-schist is a crystalline schistose aggregate of mica and quartz, varying in texture from fine-grained to coarsely crystalline. Of the two constituent minerals, sometimes the one and sometimes the other predominates, or they may be present in approximately equal proportions. The quartz occurs as granules or granular aggregates, and extends in lenticular layers, thinning- and swelling-out more or less suddenly: sometimes it assumes the form of irregular nodule-like bodies, around which the foliated mica bends. Accessory minerals are of common occurrence, such as garnet, specular iron (iron-mica), magnetite, rutile, schorl, etc.

Gneiss is a schistose aggregate of quartz, felspar, and mica (muscovite, biotite—either or both). The texture is very variable. Sometimes the rock is fine-grained and the folia are thin and even (Plate XXII. 2): in other cases the folia may be so thick, irregular, or indistinct that in hand-specimens the schistose nature of the rock may not be apparent. The proportion of the several component minerals also varies indefinitely—one or other often greatly predominating. Accessory minerals are common, such as garnet, apatite, iron-ores, schorl, rutile, etc.

Many varieties are recognised:—as, *Hornblende-gneiss*, with hornblende and often mica; *Augite-gneiss*, with a pale green pyroxene and little or no mica; *Protogine-gneiss*, with a hydrous mica in place of mica; *Graphite-gneiss*, with graphite replacing mica in whole or part; *Chlorite-gneiss*, with chlorite instead of mica; *Granite-gneiss*, with indistinct foliation; *Augen-gneiss* (Eye-gneiss) with large eye-like kernels (*phacoids*) of quartz or orthoclase (see Plate XXIII.).

The gneisses in which a foliated structure is well developed are believed to be true metamorphic rocks, and they frequently are dovetailed with or graduate into mica-schist, and even into sedimentary rocks. There are certain coarse-grained gneisses, however, which are less markedly schistose, but show a rudely parallel banded structure that seems comparable to the banded structure seen in some massive igneous rocks. Gneisses of this character may therefore be truly eruptive rocks. [The term *gneiss* is frequently applied to any coarsely crystalline granitoid schistose rock.]

Chlorite-schist is a schistose aggregate of scaly chlorite, usually with quartz, and often with felspar, talc, mica, actinolite, or magnetite—the last being frequently disseminated as perfect octahedra.

Talc-schist is a green to greenish-grey or yellow schistose rock, very soft, and with a pronounced unctuous or soapy feel. It consists chiefly of scaly talc, with which quartz and chlorite, or mica are often associated. Other minerals may be present, such as felspar, actinolite, magnetite, magnesite—the last often in large rhombohedrons. *Potstone* is the name given to a massive fine-grained to compact aggregate of talc and chlorite.

Amphibolites are either schistose or massive—their chief ingredient being hornblende or actinolite. The texture varies from fine-grained or compact to coarsely crystalline. Many other minerals may accompany the amphiboles, such as felspar, quartz, pyroxene, garnet, epidote, mica, rutile, sphene, magnetite, etc.

Hornblende-schist, a schistose aggregate of hornblende, usually contains some felspar; quartz, black mica, and other minerals may also be present. The rock is dark green to black. Usually the folia are thick, but sometimes they are very fine, and the schist then assumes almost a slate-like character. When the foliation is indistinct or not apparent we have the variety known as *Hornblende-rock*. *Actinolite-schist* is composed mainly of light or dark green actinolite, with which felspar and other minerals may be associated. When the schistose structure is obscure or wanting, we have *Actinolite-rock*. Some of the dark fine-grained amphibolites are hardly to be distinguished in hand-specimens from aphanite.

Granulite.[*]—A finely schistose holocrystalline aggregate of felspar

---

[*] There is unfortunately some confusion as to the use of the term *granulite*. Some French geologists restrict the term to a fine-grained granite in which the mica and sometimes the quartz are hardly recognisable by the unassisted eye—so that the rock seems to consist almost

and quartz, usually with small red garnets more or less abundantly disseminated. Other minerals are often present, such as biotite, muscovite, sillimanite, kyanite, or tourmaline.

Eclogite.—A medium to coarsely crystalline mixture of scaly omphacite (pyroxene), with red garnet. Frequent accessories are kyanite, white mica, smaragdite and other amphiboles, quartz, apatite, rutile, zircon, sphene, magnetite, etc. Foliation is usually obscure, and frequently wanting.

Marble is a crystalline granular aggregate of calcite, the granules being of approximately equal size (Plate IX. 2). The rock may be white or various tints of red, blue, yellow, green, or black, and it is often streaked or mottled. Scales of talc or white mica are frequently present, and such minerals as garnet, tremolite, actinolite, zoisite, biotite, etc., may be disseminated through the rock. Marble is a metamorphosed limestone, and the minerals referred to represent the original impurities of the limestone (clay, sand, etc.). In some cases very impure limestones have been transformed into a fine smoothly compact variety of *Hornfels*,* which often consists largely of an aggregate of various silicates, as tremolite, actinolite, epidote, garnet, etc., and quartz.

Serpentine is a compact or fine-grained rock which is readily scratched. On freshly broken surfaces it has a faintly glimmering lustre. It is usually of a dull greenish colour, but brown, red, and mottled varieties are not uncommon.

---

entirely of felspar—the mica and not infrequently the quartz being of microscopic dimensions. Again a granite with two micas is sometimes called granulite. Further, the term *granulitic* is commonly applied to a fine-grained rock, the crystalline granules of which present the appearance in polarised light of a brilliant mosaic. This structure is characteristic of metamorphic rocks which have been subjected to intense crushing.

* Hornfels is the name given by German geologists to certain rocks which owe their origin to thermal or contact metamorphism. They vary much in composition, texture, and structure, and get different names according to the nature of the dominant or most prominent constituent mineral, as *Andalusite-*, *Garnet-*, *Tourmaline-*, *Calc-silicate-Hornfels*, etc. Many of the rocks are very compact and so extremely fine-grained as to have a flinty or horny aspect: others are more or less conspicuously crystalline. While some are somewhat schistose, others are totally devoid of all traces of foliation. They occur usually in immediate contact with batholiths, or intrusive masses of granite, syenite, diabase, etc.

It consists mainly of the mineral serpentine, and is often traversed by numerous branching veinlets of chrysotile—a fine fibrous variety of serpentine (Plate VI.). In many cases serpentine is the result of the alteration of peridotites (olivine-rocks) or other basic igneous rocks, traces of their original mineral constituents (such as olivine, pyroxenes, amphiboles, spinelloids, felspars, etc.) being often more or less readily distinguished. In other cases the original character of the rock is not apparent. Such serpentines are often foliated, and occur interbedded with schistose rocks, where they are frequently associated with crystalline limestone.

B. Cataclastic Rocks

The origin of metamorphic rocks will be considered in Chapter XV. Here it is only necessary to point out that many of these rocks have acquired their present structure and texture under the influence of the intense strains and stresses to which the crust of the earth has been subjected. Under enormous pressure the constituent minerals of certain rocks have been rendered in a sense plastic and compelled to flow. Such rocks have consequently acquired a "shear-structure" not unlike the fluxion-structure developed in lavas. Rocks of this kind are schistose, and usually holocrystalline. In other cases, however, a rock subjected to intense compression has been merely crushed into fragments or even pulverised, without acquiring a thoroughly crystalline character. No hard and fast line separates these two kinds of structure. In point of fact, one often passes by insensible gradations into the other. Typical examples of the former are crystalline and schistose; while similar examples of the latter are fragmental or *cataclastic*. But such cataclastic rocks often exhibit a "streaky" or even schistose character, and their constituents may to some extent show a superinduced crystalline texture. In many cases, however, they consist of a compacted aggregate of smaller and larger angular and subangular fragments, forming finer or coarser brecciiform masses, which are neither crystalline nor schistose. Rocks of this type are often well developed along one or both sides of faults or dislocations of the crust (see Chapter XI.).

PLATE XXIII.

Coarse Gneiss, showing Lenticular "Eyes" or Phacoids. Nearly natural size.

[*To face page* **80.**

Mylonites.—This is the name given to more or less fine-grained cataclastic rocks. They are typically developed along the lines of great overthrusts or reversed faults, and are usually closely associated with crystalline schistose rocks, into which indeed they often pass. Most frequently they show well-developed "shear-structure"—the rock being composed mostly of minute fragments and particles with now and again larger fragments, set in a streaky groundmass of crushed materials. When the nature of the larger fragments (of minerals or rock) is obvious, not infrequently one is able to say what the original uncrushed rock may have been.

Friction- or Crush-breccia.—This is an aggregate of angular and subangular fragments, varying in size up to one foot or even more in diameter. Breccias of this kind occur in the same way as mylonites, into which they often pass. All gradations, indeed, may be traced from coarse breccia into mylonites, and from the latter into schists. When there has been considerable movement of the rock-débris and the fragments have been rolled over and more or less rounded, the rock is termed a **friction-conglomerate**. Although friction-breccias are best developed in regions where the rocks have been subject to much compression—to folding and great dislocations and displacements—and where frequently metamorphism is more or less pronounced, they are nevertheless not confined to such regions. Faults traversing strata of all kinds are not infrequently accompanied by breccias. Sometimes these are confined to a line of fracture, filling up the space between the two walls of a fault; while in other cases the rocks forming one or both walls of a fault have been jumbled, shattered, and brecciated. The stones in such **fault-breccias**, as they are termed, are not infrequently rubbed smooth and striated on one or more sides.

Determination of Rocks in the Field

The beginner who casts his eye for the first time over a good collection of rock-specimens is apt to be dismayed by the numerous species and varieties with which he is expected to become acquainted. The coarser grained rocks, whether they be derivative, igneous, or metamorphic, do not appear to present much difficulty. He may feel hopeful that, with ordinary care, he will eventually learn to distinguish one from another. It is the fine-grained and compact stones, in which the naked eye may fail to recognise the nature of the component ingredients, that chiefly puzzle him. How are the various compact igneous rocks to be distinguished from each other, or indeed from other compact rocks of any kind? One may, of course, with the help of a pocket-lens, be able to detect the character of some fine-grained rocks, but in the case of many others a careful microscopical examination of thin slices will be absolutely necessary before one can be sure of their nature. It must be admitted, indeed, that we cannot know all about rocks, whether they be coarse-grained or fine-grained, before we have submitted them to careful scrutiny under a microscope. The student who does not desire to specialise as a petrologist, however, may nevertheless come to be very knowing in the matter of rock-determination by following a few simple rules or methods.

In attempting to determine a rock in the field, the beginner should be careful, in the first place, to examine fresh surfaces. Rocks which have been exposed to the weather are always more or less altered, the weathered crust being thick or thin, according to the nature of the rock, and the length of time it has been subject to the mechanical and chemical action of the superficial agents of change. It need hardly be said, therefore, that the fresh rock may differ very much from the crust which covers it. Assuming, then, that a fresh surface has been obtained, the student endeavours to ascertain to which of the great classes the rock belongs—is it crystalline or fragmental? If it be coarse-grained, he should have no difficulty in answering this question. Should it be crystalline, the crystalline ingredients will either be confusedly aggregated or arranged in parallel lenticular folia. In the former case it is probably an igneous rock * ; in the latter case it is a schist. If, on the other hand, the rock be composed of rounded waterworn materials, it is a conglomerate of some kind ; but if the included fragments be angular, it is a breccia. It is obvious, therefore, that in the case of coarse-grained rocks the first step towards determining them is simple enough. With finer-grained rocks, however, it is otherwise. At first the observer may have some difficulty in discriminating between the mineral constituents of such rocks even with the help of a lens. It is a good plan to pound a chip of the fresh rock with the hammer, and reduce it by rubbing to a gritty powder. In the case of crystalline igneous rocks and many schists, this process often succeeds in separating the rock-constituents from each other more or less completely, so that they can be turned about with the point of a knife in all directions, and subjected to a more thorough

---

* It might be, however, coarsely crystalline limestone, dolomite, or anhydrite. These rocks are *simple—i.e.* they are composed throughout of one mineral ingredient, and could readily be determined by the simple tests mentioned on pp. 28, 29. A coarsely crystalline igneous rock, on the other hand, would usually be recognised by its composite character, and by the fact that its constituent minerals were not apparently affected by dilute acid.

examination than is possible with the minerals locked together in a hand-specimen. A magnet drawn through the powdered rock will take up any magnetite that happens to be present. There should be no difficulty either in differentiating between minerals with good cleavage, and those which do not possess this property. Fragments of the former will be distinguished by their flat lustrous faces, while the latter will be quite irregular in shape. Should the rock be too fine-grained to allow of the rough separation of its constituents for examination with the lens, the powder will yet yield much information when studied with a low power under the microscope. A little should be placed on a glass slide, with a drop or two of water or oil added, and another glass-slip laid atop. By gently rubbing the upper slip over the powder, the grains can be still further reduced, and the individual constituents more thoroughly isolated. In this way the observer will often get evidence sufficient to enable him to pronounce on the true nature of the rock. All the common rock-forming minerals may be detected by this simple process just as readily as they can be by the examination of carefully prepared rock-slices.

For purposes of determination in the field the more commonly occurring rocks (those, namely, which enter most largely into the formation of the earth's crust) may be grouped under these four heads : 1. Argillaceous Rocks, 2. Calcareous Rocks, 3. Siliceous Rocks, and 4. Felspathic Rocks.

Argillaceous and **Calcareous Rocks** are readily recognised. Their hardness ranges from less than 1 up to 3·5, and they are thus all readily scratched with a knife—many of them even with the finger-nail. A very soft rock, having a dull earthy aspect, and which when moistened is plastic, must be a *clay*. Should the rock be somewhat harder, and occur in thin irregular laminæ, which may or may not cohere, it is an *argillaceous shale*. If the shale, when rubbed down, be more or less gritty from the presence of grains of quartz, it is an *arenaceous shale*. Or, should it be black, and without gritty matter, it is most probably a *carbonaceous* or a *bituminous shale*. Or, again, if it be lighter in colour and effervesce with cold dilute hydrochloric acid, it is a *calcareous shale*. *Clay-slate* will be readily recognised by its structure—splitting, as it does, into firm plates along the superinduced planes of cleavage. Argillaceous rocks, when breathed upon, emit a peculiar earthy odour, and although this character is not confined to such rocks, nevertheless if a fresh rock, having this pronounced odour, be readily scratched, and present a dull earthy aspect, we may feel tolerably sure that it is argillaceous.

Limestones are all easily scratched with a knife (the hardness being 3 or less), and effervesce briskly with cold dilute acid. If the rock be relatively pure, it will weather with only a thin (generally yellowish or brownish) pellicle for a crust ; if it contains many impurities (clay, sand, iron-oxides), the weathered crust will be correspondingly thick. *Dolomitic limestone* is slightly harder (3 to 4) than common limestone. It effervesces very slowly with cold acid, but more briskly when the acid is heated.

The **Siliceous Rocks** are distinguished especially by their hardness.

Some varieties are very fine-grained or compact, so that the constituents are not visible even with the help of a lens. Rocks of this kind (such as *flint* and *chert*) usually occur in the form of nodules, irregular aggregates, veins, or layers, especially in limestones. They are compact and homogeneous, have usually a dull, horny-like aspect, cannot be scratched with the hardest knife, and do not effervesce with acid. *Lydian-stone* is another close-grained siliceous rock, which usually contains carbonaceous matter, so that it is dull grey or even black. It is commonly associated with greywacké, clay-slate, or schistose rocks, and is often traversed by numerous ramifying veinlets of white quartz. These characters and its great hardness suffice to distinguish it. All the compact siliceous rocks referred to are differentiated from certain compact igneous rocks (*felsites*) with which they might possibly be confounded, by their infusibility before the blowpipe.

Granular siliceous rocks are typically represented by *sandstones* and *conglomerates*—the determination of which presents no difficulty even to a beginner. The hard, round, subangular or angular grains of a sandstone consist chiefly of quartz. The student should be able, with the help of his pocket-lens, to detect the fragmental character of even the finest-grained sandstone. The bedded character of the rock and the general aspect of the strata with which it is associated should leave him in no doubt as to its nature. Sandstones, of course, differ greatly as regards their hardness and durability—some are much more closely compacted than others. The nature of the cementing material, as we have already learned, also varies. It is just possible that a fine-grained *oölitic limestone* might be mistaken for a sandstone, but the relative softness of the former, and the readiness with which it effervesces with acid, at once betray its character. It is unnecessary to add a word as to the determination of *conglomerates*—everyone is familiar with the appearance of such consolidated gravels. The only other eminently siliceous rock that calls for notice is *quartzite*. This is simply a much indurated sandstone—the grains of the rock being cemented by silica. It is, therefore, exceedingly hard, and breaks with a splintery or conchoidal fracture, and usually shows a somewhat glassy lustre. The student may note further that in the case of quartzite and many sandstones which have silica for their binding material, the component grains are so firmly cemented together that they do not separate but break across, so that the face of the fracture is smooth and often glistening or glassy ; whereas, in ordinary sandstones, a fresh fracture is dull and has a rough feel, owing to the rock separating between the grains and not through them.

The **Felspathic Rocks** offer a wide range as regards hardness, texture, and structure. Some are soft and more or less earthy ; others are hard, distinctly crystalline, fine-grained, smoothly compact, or glassy ; while yet others are fragmental. Again, the crystalline varieties may be schistose, or their ingredients may be confusedly aggregated. Many of the harder felspathic rocks cannot be scratched with a knife, but usually their hardness is less than that of the siliceous rocks. In the fresh state none of them effervesces with acids.

(*a*) **Highly Vitreous Felspathic Rocks** are easily determined by their lustre. A glassy rock showing a uniform texture, either black or some dark colour, which breaks usually with a conchoidal fracture, and is translucent on thin edges, is most probably *obsidian. Pitchstone* may generally be distinguished from obsidian by its pitchy or resinous lustre, by its fracture, which is more frequently splintery than conchoidal, and by its feebler translucency. Its colour is variable—dark or light shades of green, brown, red, yellow, etc. Obsidian and pitchstone are acid glasses, and are, therefore, often found passing or graduating into acid hemicrystalline rocks. The *basic glasses* are associated with such rocks as basalt, into which they pass. This is often seen, for example, along the marginal surfaces of dykes and sills where, owing to the chilling influence of the surrounding rocks, the molten mass has cooled too rapidly to permit the development of crystallisation.

(*b*) **Compact** and **Fine-grained Felspathic Rocks** are usually very difficult to determine in the field; indeed, it is often quite impossible to tell one from another in hand-specimens. The mode of their occurrence, the general character of the rocks with which they are associated, their structural features, and their mode of weathering, will often aid one in forming an opinion as to their nature. But only a microscopic examination will suffice to determine precisely what the rocks really are. The following notes on some of the more commonly occurring compact felspathic rocks may, however, be of use to the beginner.

A fine-grained or smoothly compact rock, which on fresh surfaces can barely be scratched with a knife or not at all, which is not affected by acid, and is fusible in thin splinters, is probably a *felsite*. Should it contain more or less numerous phenocrysts of felspar and quartz, and possibly other minerals, such as biotite and hornblende, it is most likely a *quartz-porphyry*. Rocks of this type usually weather with a thin white or light-coloured crust. Their colour is very variable, but generally not dark—white, grey, yellow, brown, or red, being the prevailing tints. Quartz-porphyry might sometimes be confounded with rhyolite—a hemicrystalline rock. *Rhyolite*, however, is not nearly so common or widely distributed a rock as the former. It often exhibits a finely cavernous character—the cavities being lined with quartz or some other form of silica—a structure which is not characteristic of quartz-porphyry. While the groundmass of a rhyolite not infrequently has the smoothly compact or dull horny-like aspect of that seen in felsites and quartz-porphyries, it is more commonly glassy, enamel-like, or porcellaneous, and very often highly perlitic; but spherulitic and fluxion structures are more especially characteristic. Scattered through this matrix are conspicuous crystals of glassy felspar, granules of quartz, and small crystals of some dark ferromagnesian mineral (usually biotite or augite). The rock has often a peculiar, harsh, rough feel. All the *highly acidic felspathic rocks* have, on fresh, unweathered surfaces, a hardness of 6·5 or thereabout; they are usually light-coloured, and generally weather with white or light-coloured crusts, which are relatively thin, and more or less well defined, but not readily detached from the rock.

The *less acidic felspathic rocks*, like the more acid types, are often fine-grained and compact—either sparingly porphyritic or without any conspicuous phenocrysts. The commonest varieties in this country are the *andesites* and *porphyrites.* These are more frequently dark-coloured than the highly acid rocks, but are on the whole lighter in colour than the basic rocks of which basalt may be taken as the type. Their hardness varies on fresh surfaces from 5·5 to 6; but as few of our andesites are without some alteration, their hardness is often less than 6, so that they can be scratched with a knife. The compact varieties are generally bluish or greenish, and tend to weather with a thinnish light-coloured crust, which is often more or less ferruginous (yellow or brown). But when they contain a considerable percentage of ferromagnesian minerals, they are darker coloured, and the crust is thicker and more markedly rusty in aspect. Varieties of this kind can hardly be distinguished from similar fine-grained basalts, although there is almost always something in the general aspect of an andesite as seen in the mass, such as the character of its jointing and its mode of weathering, which, after some experience, the student will come to recognise.

Compact *phonolites* are generally light-coloured—white, grey, bluish, or yellowish—and emit a bell-like clink when struck with the hammer. They are often readily split up into thin flags, and weather with a well-defined white crust.

Fine-grained *trachytes* are commonly light or dark grey rocks, having the harsh or rough feel already referred to as more or less characteristic of some rhyolites—which they in this and other respects closely resemble. They are differentiated from rhyolites chiefly by the absence of quartz. There is nothing in the mode of their weathering, however, to distinguish them from rhyolite. Neither trachytes nor phonolites are common rocks in Britain. Large crystals of sanidine are common in trachytes.

Compact *diorite* varies in colour from greyish-green to dark green and black, and is known as *aphanite*—the green colour being due to its hornblende, and not necessarily to the presence of such decomposition-products as serpentine and chlorite. The fresh rock has a hardness of about 6. Such a rock closely resembles an amphibolite, from which, however, it may sometimes be distinguished by its weathering. If the rock be a diorite it will weather with a rusty crust, the inner portion of which (that, namely, which is nearest to the relatively unweathered rock) will exhibit effervescence with acid—thus revealing the presence of calcium carbonate—one of the products of the decomposition of the constituent felspar.

Compact and fine-grained *basic rocks* are widely distributed in this country. They are chiefly *basalts*, and in fresh exposures are very dark blue to black in colour. They have a hardness of 5 to 6, but when the rock is weathered the hardness may be much less. Very often a few isolated grains or an occasional granular aggregate of green or yellowish-green olivine may be seen, even in the most smoothly compact basalt. The jointing of the rock is generally more regular than that of the compact and fine-grained acid igneous rocks—basalt being frequently divided by prismatic joints, and thus rendered columnar in structure. Basalt weathers with a thick rusty or yellowish-brown crust, which often exfoliates in concentric shells. Not infrequently, owing to the alteration of its ferromagnesian constituents into serpentine and chlorite, the rock assumes a dull, dirty, greenish colour.

(*c*) **Coarse-grained Hemicrystalline Felspathic Rocks.**—These rocks may show little trace of a base or groundmass, and will often puzzle the beginner, for it is the character of the finer grained matrix that in many cases differentiates one type of igneous rock from another. But with care and patience he may hope to distinguish most of those the essential components of which can be clearly seen with or without the aid of his pocket-lens. Very often the nature of the rock will be suggested by the aspect of its weathered crust. When this is light-coloured, and the rock has a white, greyish-white, or yellowish-white, earthy, chalky, or clay-like appearance, he may suspect that he is dealing with a more or less acidic rock. Should it be a *quartz-porphyry* or a *rhyolite*, it will show either granules or crystals of quartz, which may be readily separated from the decomposed matrix in which they are embedded. If, on the other hand, no trace of quartz be visible, then the rock will probably be *orthoclase-porphyry*, *trachyte*, *phonolite*, or *andesite*. In the case of andesites, however, it must be remembered that the weathered crust is not infrequently rather brown and rusty. Coarse-grained *basalts*, like the finer grained and compact varieties, are in like manner often recognisable by their conspicuous dark rusty brown or yellowish crusts. Removing the weathered crust, the character of which may have suggested the type of rock he is examining, the observer carefully scrutinises the component minerals in the usual way. If it be a basalt-rock, it ought to show on a fresh fracture an aggregate of striated felspars—numerous glassy-like rods—with entangled crystals and crystalline granules of dark or black minerals (augite and magnetite), and frequently scattered granules of a greenish mineral (olivine). An ordinary coarsely crystalline *andesite* will consist almost exclusively of laths or rods of a similar felspar, olivine being absent, and dark ferromagnesian minerals either apparently wanting, or, if present, not nearly so numerous as in a basalt-rock. When such minerals abound, then, without careful microscopic examination, it would be impossible to say whether the rock was basaltic or andesitic. The *trachytes* and *rhyolites*, as we have learned, are usually lighter coloured rocks than the andesites and basalts. Both are commonly distinguished by their rough feel. Their dominant felspar is orthoclase, of which the phanerocrystalline types appear to the naked eye to be almost entirely composed. Usually, however, we may detect small crystals of dark ferromagnesian minerals more or less sparingly entangled among the felspar crystals. Very often, too, large phenocrysts of glassy orthoclase (sanidine) are present. Should quartz be also present, then the rock is a rhyolite; if it be wanting, we have a trachyte. Decomposing *phonolite* can hardly be distinguished from weathered trachyte. But the coarser grained kinds, on freshly fractured surfaces, usually show well-defined tabular crystals of glassy felspar, often arranged in parallel positions, and having as common associates six-sided prisms of nepheline, and not infrequently prisms of some pale green pyroxene and small crystals of magnetite. But dark-coloured minerals are not as a rule so common as in trachyte. The rock is prone to become decomposed, the decomposition-products, in the form of various zeolites, appearing in cracks and cavities. *Quartz-porphyries*, which, to the unassisted eye, may seem to consist exclusively of crystalline ingredients, have a granitoid aspect. On fresh faces the observer will readily distinguish the two dominant minerals, orthoclase and quartz, while on weathered faces the presence of a groundmass is often revealed by earthy or clay-like matter entangled between the quartz and the weathered felspar.

(*d*) **Coarse-grained Holocrystalline Felspathic Rocks** offer on the whole fewer difficulties to the beginner. If he has already learned to recognise the common rock-forming minerals, he should be able to distinguish the several essential constituents of such rocks as coarse-grained granite, syenite, diorite, gabbro, and dolerite. The finer grained holocrystalline varieties will sometimes be diagnosed with difficulty. In such cases he will often be aided by the appearances presented by the weathered crusts. The felspars, he will remember, tend to be decomposed into an earthy or clay-like substance, which will be lightly or more darkly tinted according to the proportion of decomposing ferromagnesian constituents with which they are associated.

(*e*) **Fragmental Igneous Rocks** vary greatly as regards texture, some being exceedingly fine-grained, while others are composed of an aggregate of larger and smaller blocks. The finer grained varieties are usually of an earthy or clay-like aspect and readily scratched ; many, indeed, are so slightly compacted that they may be disintegrated between the fingers. Such rocks may show scattered through them flakes of mica, and broken crystals of various volcanic minerals. They are usually well-bedded, having been arranged and spread out in layers by aqueous action. For the same reason they often dovetail with or pass into ordinary aqueous rocks, such as sandstones and shales. Many tuffs, again, consist largely of finely comminuted débris of igneous rocks, either of one or of different kinds ; such tuffs commonly contain cinders and lapilli of lavas. Rocks of this class are most usually interbedded with lava-form igneous rocks. The coarser agglomerates and volcanic breccias may also occupy a bedded position, but they very frequently occur in the pipes of old volcanoes or in masses immediately surrounding these.

(*f*) **Crystalline Schists.**—Their determination is, as a rule, not hard. Where the several ingredients are conspicuous, and the rock tolerably fresh, its diagnosis should not be more difficult than that of a coarse-grained holocrystalline igneous rock. Not infrequently, however, the component crystals of a schist are very small individuals, and so closely intermingled, that they can hardly be distinguished even with the help of one's pocket-lens. In such cases, should the rock be a pale whitish-green colour, have a marked soapy feel, and be easily scratched, it will probably be *talc-schist*. *Chlorite-schist* is also easily scratched, but is dark green and not quite so unctuous to the touch. *Hydro-mica-schist* is likewise soft, pale white or greenish, and with only a slightly soapy feel. A rock composed of a fine-grained schistose aggregate of dark green or greenish-black fibrous scales is probably *hornblende-schist;* a similar aggregate of dark or light green acicular or ray-like fibrous crystals is probably *actinolite-schist.* The other common schistose rocks—mica-schist and gneiss—should not be hard to distinguish, even in fine-grained varieties—seeing that the constituent minerals are all easily recognisable, especially on the edges of the folia.

The Argillaceous, Calcareous, Siliceous, and Felspathic rocks undoubtedly form the bulk of the earth's crust—the other kinds of rock not included under one or other of those heads taking quite a subordinate place. Many of them, however, are of great economic importance—conspicuous members of the series being the coals, carbonaceous compounds of all kinds, ironstones, and various minerals, which now and again play the part of rocks. Among the latter are rock-salt, gypsum, anhydrite, apatite, etc., but as the distinguishing characters of the minerals have already been given, they need not be repeated here. If the student can recognise the minerals in small specimens, he should not have much difficulty in diagnosing them when they appear as massive aggregates.

The specific gravity of rocks is not infrequently a character of some importance, and of no little assistance in their determination. The following table gives the average specific gravity of a number of representative igneous rocks * :—

Granite . . .	2·6—2·7	Diorite	2·7—2·9
Quartz-porphyry . .	2·4—2·6	Andesite	2·4—2·7
Rhyolite . . .	2·4—2·5	Gabbro	2·7—3·0
Obsidian . . .	2·0—2·3	Dolerite	2·7—3·0
Pitchstone . . .	2·3—2·4	Basalt	2·8—3·1
Syenite . . .	2·6—2·9	Nepheline-basalt .	2·9—3·0
Orthoclase-porphyry .	2·6—2·7	Leucite-basalt . .	2·8—2·9
Trachyte . . .	2·4—2·6	Limburgite . . .	2·8—3·0
Phonolite . . .	2·5—2·6	Peridotites . . .	3·0—3·5

---

* The student who desires to take the specific gravity of a rock cannot do better than employ the simple and satisfactory instrument described in Appendix C.

CHAPTER VI

FOSSILS

Modes of Preservation of Organic Remains. Kinds of Rock in which Fossils occur. Fossils chiefly of Marine Origin. Importance of Fossils in Geological Investigations. Climatic and Geographical Conditions and Terrestrial Movements deduced from Fossils. Geological Chronology and Fossils.

HITHERTO we have been concerned with rocks mainly as aggregates of mineral matter, and only a passing reference has been made to the fact that certain derivative accumulations contain *fossils*—the remains and traces of formerly living creatures. We have seen, it is true, that some kinds of rock, such as coal and limestone, consist chiefly of the débris of plants and animals, but we have now to realise that almost every variety of derivative rock may be more or less fossiliferous, and that traces of former life have been met with, now and again, even in certain igneous and metamorphic rocks.

When a plant or animal, or any portion of either, is buried in sediment, it becomes subject to decomposition. This process usually results in the destruction of all organic compounds of carbon and nitrogen, and even the harder and more durable parts undergo some change, and may eventually become disintegrated, and entirely disappear. Certain chemical changes, however, may supervene before the process of destruction is completed. In many cases, for example, carbonisation takes place—various gases are given off, and the organic tissues are gradually transformed into carbon. Or mineral matter may be introduced in solution so as to fill up all the cavities of the original structures, or even to replace completely the substance of the organism. Fossils, therefore, are met with in all states of preservation. Exceptionally, the entire organism has been preserved with little or practically no change of the original substance—the bodies having been protected from decomposition by the nature of the materials in which they have been entombed. As examples may be cited the carcasses of the extinct mammoth and woolly rhinoceros which, long ages ago, were sealed up in the frozen earths and ice of Northern Siberia, so that when in recent times they became exposed, owing to the gradual dissolution of the medium in which they had been buried, their bodies were in so fresh a state that dogs devoured the flesh. Insects, spiders, and plants, have similarly been completely preserved in amber (fossil gum or resin); but, in most cases, these would appear to be more or less carbonised. The more common methods of preservation, however, are as follows:—

Incrustation.—The organism under certain conditions is enveloped in a covering of mineral matter. Calcareous tufa, for example, is often precipitated upon plants growing near springs containing much calcium-carbonate. In the case of thermal waters siliceous sinter may be the incrusting substance. Vegetable and insect remains preserved in this manner are often more or less carbonised, or they may be entirely decomposed and dissipated, leaving merely hollow moulds behind them.

Carbonisation.—Plant-remains and chitinous animal structures, without having been previously incrusted, frequently undergo carbonisation—a deoxydising process which takes place under conditions permitting of only a limited access of air. Thus plants accumulated in marshy ground, or on the floor of lake or estuary, or buried in mud, etc., tend to undergo a kind of distillation whereby the oxygen and other gases are gradually eliminated—the carbon in this way becoming concentrated.

Moulds and Casts.—The substance of a buried organic body may be entirely dissipated, and only a mould of it remain. Should this mould be subsequently filled with mineral matter, a cast showing the external form of the original will be produced. This is a common kind of fossilisation. Many fossil shells, for example, are simply casts, and do not contain a particle of the original substance. When an empty bivalve or univalve shell is enclosed in a deposit, the sediment usually at the same time fills the vacuity. Afterwards, the shell itself may be gradually dissolved and removed by percolating water. The cavity thus formed may be subsequently reoccupied by mineral matter, and in this way a perfect cast will be produced. Not infrequently, however, the space left by the shell remains unfilled, containing in its centre the stony kernel which formerly occupied the interior of the original. Should this kernel not adhere to the matrix, it will rattle, like a nut in its shell, when the specimen containing the fossil is shaken.

Permeation and Molecular Replacement. — Mineral matter has often thoroughly permeated an organic body, and filled up all its pores and cavities—a process which has usually been preceded, accompanied, or followed by carbonisation. Not infrequently, under these conditions, the original substance itself is more or less molecularly replaced by mineral matter, with partial or perfect preservation of the internal structure. This kind of fossilisation is well illustrated by some specimens of silicified wood, the minutest structures of which have been so completely replaced that a slice of the specimen, viewed under the microscope, reveals as much as a section of the original wood itself could have shown. Permeation and molecular replacement may be exemplified by one and the same fossil, so that the two kinds of fossilisation are frequently hard to distinguish. An organic body which is permeated and molecularly replaced by mineral matter is a true petrifaction.

In cases of true petrifaction, the replacing mineral is usually either silica (mainly chalcedony or opal) or calcium carbonate. The same substances also play the most important part in the formation of incrustations and casts, which is just what might have been expected when we remember how very widely calcareous and siliceous solutions are diffused. Other substances, however, not infrequently replace organic remains, such as the compounds of iron (pyrite, marcasite, hæmatite, limonite, and siderite), and, less frequently, gypsum, barytes, fluor-spar, and various metals and metallic compounds.

It is not only the relics and remains of plants and animals which are termed fossils, but any recognisable trace of their former existence—any impressions or tokens left behind them—whether it be footprints, tracks, or trails, burrowings, castings, or coprolites, or even the markings traced on sediment by the waving to-and-fro of seaweeds, etc.—are all equally fossils.

Kinds of Rock in which Fossils occur.—As a rule, the best preserved fossils are met with in the finer grained sedimentary rocks, as in marls, limestones, clay and shale, and fine argillaceous or calcareous sandstones.

Calcareous Rocks.—Argillaceous limestones and marly shales are often highly fossiliferous, and the fossils are usually well preserved. But pure limestones, which have become more or less crystalline, frequently appear to be poor in organic remains, so that when a fresh fracture of the rock is obtained, few or no traces of any structure may be visible. On surfaces which have been for some time exposed to the weather, however, fossils not infrequently project in bold relief—the limey matrix in which they are embedded offering less resistance to atmospheric action. The same phenomena characterise many dolomitic limestones.

Argillaceous Shales.—Not infrequently these are rich in fossils—their impervious character having doubtless tended to the preservation of the remains. Some shales, however, are very barren, or the few fossils present may be included in nodular concretions of calcium-carbonate, siderite, or other substance.

Sandstones are not so frequently fossiliferous as shales, for which there are at least two reasons. First, a sandy sea-floor, owing to frequent or constant movement of the sediment, is not favourable to sedentary forms of life, and is therefore avoided by organisms which cannot shift for themselves. An ordinary siliceous sandstone might therefore be expected to be somewhat barren. Second, the permeable character of sandstones must favour the subsequent passage of percolating water which so frequently dissolves and removes organic bodies. Massive thick-bedded quartzose sandstones and red sandstones are, as a rule, singularly poor in organic remains. Certain thin-bedded argillaceous and thick-bedded calcareous sandstones, however, are not infrequently highly fossiliferous—and this is especially the case when the sandstones occur in beds alternating and interosculating with dark carbonaceous or lighter coloured calcareous shales.

Conglomerates are generally unfossiliferous, or, if fossils are present, these are usually more or less rolled and water-worn. For example, we may obtain, in some Carboniferous and Jurassic conglomerates, worn fragments of the trunks and branches of trees—but the more delicate twigs and leaves are absent. So, again, in gravels and conglomerates of Pleistocene and Recent age, only the more resistant large bones and teeth of mammals are ever met with, and they are often rolled and broken. There are exceptions to every rule, however, for, now and again, tolerably well-preserved shells do occur in conglomerates.

Volcanic Tuffs.—In certain bedded volcanic tuffs fossils occur, but this is not common. Plant-remains have even been encountered in the coarse tuffs and agglomerates that occupy the throats or necks of certain ancient Carboniferous volcanoes in Scotland. Probably these represent trees, etc., which grew upon the slopes of the old cones after the volcanoes had become extinct. More rarely still, charred fragments of trees have been met with enclosed in the lower portion of an ancient lava.

Schistose Rocks.— It need hardly be said that these rocks are usually destitute of organic remains. Nevertheless, fossils are occasionally present in schists, as in certain metamorphic Silurian rocks in the neighbourhood of Christiania, and in the highly crystalline schists of Liassic age which enter into the structure of the Central Alps.

Fossils differ much not only in regard to the state of preservation of their internal structure, but also of their external form. In many cases, they have been much compressed—what were formerly cylindrical branches, for example, have often been flattened, so as to give lenticular sections when cut across. In limestones, marly shales, and calcareous sandstones, shells, corals, etc., usually retain their original shapes; while in argillaceous shales, fossils of all kinds are apt to be more or less flattened—a rule, however, which has many exceptions. In clay-slates and rocks which have obviously been subjected to much compression, fossils are usually highly distorted and often recognised with difficulty.

By far the great majority of fossils are of marine origin, most of the sedimentary formations in which they occur having been deposited upon the floor of the sea. Freshwater and terrestrial accumulations form an inconsiderable proportion of the series of stratified rocks, so that relics of the occupants of former rivers, lakes, and dry lands are of relatively infrequent occurrence. At the present day aquatic animals largely exceed terrestrial animals in number, and the same was the case in earlier ages. On the other hand, in the world of to-day plants are mostly terrestrial forms, and although we know very little of the land-plants of the earlier geological periods, there is no reason to doubt that terrestrial floras have, for unnumbered ages, greatly surpassed marine floras in abundance and variety. The conditions for the accumulation and preservation of plants in the still waters of lakes, lagoons, and estuaries, are upon the whole more favourable than those that obtain upon the sea-floor. Moreover, many seaweeds, with their loose, cellular tissues, are more readily decomposed than the great majority of the land-plants with their more enduring vascular tissues. For these and other reasons terrestrial plants occur in places more abundantly and in a better state of preservation than seaweeds. Nevertheless, impressions and casts of the latter are not uncommon in strata of all ages, and hence it may be said that seaweeds are more widely distributed as fossils than land-plants.

It is obvious, therefore, that from a general point of view, marine organic remains are of most importance to the student of historical geology. It is unquestionable that the records of past times are preserved chiefly in the marine formations of the earth's crust. It is by studying these records that we are able to follow the main lines along which the world's development has taken place. The histories revealed by freshwater and terrestrial accumulations are, as it were, only episodes, although these episodes are usually most interesting and instructive. Now and again, indeed, they may be said to constitute more or less complete chapters of the general world-history. They tell us of the life of the land, of which only sparse traces are met with in marine formations. It is obvious, indeed, that the great majority of land-plants and animals must necessarily disappear without leaving any trace behind. The surface on which they live is pre-eminently a region of disintegration and denudation rather than accumulation. It is, therefore, only under exceptional circumstances that relics of land-life can be preserved. The sea, on the other hand, is *par excellence* the region of accumulation. The creatures which live and die there are thus much more likely to be represented. It is simply for this reason that the records of marine life are so much more continuous and abundant than those of land-life. Hence relics of land-plants and animals are, generally speaking, of relatively less value to the geologist for the purpose of comparing and correlating separate areas of fossiliferous strata. Nevertheless, some of the most absorbingly interesting and fascinating chapters in the world's history have been rescued from terrestrial and lacustrine formations. It must also be noted that in certain cases it has been possible to correlate widely separated areas of terrestrial and freshwater deposits by means of their fossils. This holds specially true for certain systems and stages, as in the case of the Coal-measures, the coals and lignites of later age, and the estuarine and freshwater deposits of Secondary, Tertiary, and more recent times.

A glance at the several great phyla of the animal kingdom will serve to show the relative importance to geologists of marine organic remains.

Protozoa.—Among these lowly organised forms are many which possess calcareous or siliceous hard parts. Members of this phylum therefore occur in great abundance in marine formations of all ages.

Porifera (Sponges).—A few of the living types are of freshwater habitat, but the great majority are marine, and the same was the case in earlier ages. As many sponges are furnished with a calcareous or a siliceous skeleton or framework, they are somewhat common fossils in many marine deposits.

Cœlenterata.—These also are essentially marine. The phylum includes the corals, which are among the most abundant fossils—often forming immense sheets and masses of limestone.

Echinodermata.—This is another great division of marine creatures, amongst which are star-fishes, sea-urchins, and stone lilies—the calcareous tests and skeletal remains of which are among the most frequently occurring fossils in many formations.

Annelida (Worms).—These are known as fossils chiefly by their tracks and castings—being for the most part soft-bodied creatures, they have rarely been preserved. As these tracks and castings occur chiefly in marine sedimentary rocks, it is very doubtful if any of them indicate earthworms. The "tubes" formed by many marine annelids are often met with as fossils.

Molluscoidea.—These are among the commonest and most abundant fossils. One great division (Polyzoa) comprises the lace-corals and sea-mats, which are chiefly marine, and, as fossils, often occur associated with other marine organisms. The other great division (Brachiopoda) is exclusively marine, and includes the lamp-shells, etc.—one of the most important types of life with which the student of historical geology has to deal.

Mollusca.—The same holds true with the marine mollusca, which are more or less abundantly represented in every great system of strata. Not only are they of prime importance by reason of their abundance as regards genera, species, and individuals, but their shells, like those of the brachiopods, appear often in a comparatively perfect state of preservation. Freshwater shells and land-snails are of much less frequent occurrence as fossils.

Arthropoda.—This phylum embraces lobsters, crabs, scorpions, spiders, centipedes, and insects, and is of great value to the geologist—the crustaceans more especially, for a large proportion of these being marine, they are well represented by fossils. Some of the extinct types, as Trilobites, for example, are characteristic fossils of the older geological systems. Freshwater and terrestrial forms are not so commonly encountered, since they are largely confined to freshwater deposits and to lignite- and coal-bearing strata.

Vertebrata.—This great phylum is most numerously represented by marine fishes. Marine types of reptiles and mammals also occur now and again, but with the exception of the fishes vertebrate remains of any kind are sparingly met with. Remains of birds and land-mammals are almost confined, as might have been expected, to freshwater and terrestrial accumulations.

Importance of Fossils in Geological Investigations.—It need hardly be said that the study of fossils to the biologist is of surpassing importance. Such study, indeed, cannot be ignored by him if he would understand the life-history of existing types. But it is not with that side of palæontological inquiry that the practical or field-geologist is mainly concerned. He values fossils chiefly for the help they yield him in his endeavours to realise the conditions under which sedimentary rocks were formed, and to ascertain the chronological sequence of the strata.

Climatic Conditions deduced from Fossils.—Individual fossils, if of existing species, and occurring *in situ*, may give valuable evidence as to former climatic conditions. Two examples may be cited. Certain relatively recent accumulations of calcareous tufa, occurring at La Celle near Paris, have yielded well-marked remains of the Canary laurel (*Laurus Canariensis*). There is no doubt, therefore, that this plant formerly flourished in Northern France. It is no longer a native of that country, however, its headquarters being in the Canary Islands, where it is found flourishing luxuriantly in the woody regions with a northern exposure, between a height of 1600 feet and 4800 feet above the sea—regions which are nearly always enveloped in steaming vapours, and exposed to the heavy rains of winter. The temperature there keeps above 69° F. during the greater part of the year, rarely falling in the winter months below 59° or 60°, and only on the coldest days reaching 49°. The presence, therefore, of this variety of laurel in the Pleistocene tufa of La Celle shows that the winter climate of Northern France must formerly have been very mild. The laurel in question is most susceptible to cold, and as it flowers in the winter season, it is obvious that repeated frosts, such as are now experienced in the north of France, would prevent it reproducing its kind. Another and more familiar example of the important evidence which is sometimes afforded by fossil remains of existing types is that of the Polar willow (*Salix polaris*)—a characteristic arctic plant, living in Northern Lapland, Spitzbergen, etc. This dwarf willow has been met with again and again in Pleistocene deposits in Southern Sweden, Denmark, England, etc., and in various parts of Central Europe, as far south as Bavaria and the low-lying parts of Switzerland. It cannot be doubted, therefore, that the appearance of the Polar willow so far south of its present habitat, points to a very considerable climatic change—arctic conditions would seem to have prevailed at a relatively recent period in what are now the temperate latitudes of our continent.

It is obvious, however, that the evidence of fossils as to climatic conditions must be much stronger when a whole assemblage of organic remains tells the same tale. In the case of the tufa of La Celle, for example, the Canary laurel is accompanied by the remains of many other plants, as well as by shells of land-snails, each of which is indicative of a milder and more equable climate than now characterises Northern France. And the same is the case with the Polar willow, the evidence supplied by it being fortified by that of other high northern plants, and by the relics of such animals as lemming, arctic fox, etc.

Great caution must be exercised in deducing climatic conditions from the occurrence of extinct forms of life. For these, even when they very closely resemble living types, need not have existed under similar conditions. For example, so long as the mammoth and woolly rhinoceros were only known from their skeletal remains, they were generally supposed to have existed under the same climatic conditions as their living representatives. We know now, however, that each was provided with a thick woolly and hairy covering, and was capable, therefore, of withstanding the rigours of a northern winter.

In dealing with fossils consisting largely of extinct species, it is the general facies of a flora and fauna, and not individual forms, that are to be specially considered. For example, the London Clay (Eocene) has yielded a large number of types having a tropical or subtropical aspect. Amongst the plants are forms of sarsaparilla, aloe, amomum, fan-palms, fig, liquidambar, magnolia, eucalyptus, cinnamon, various proteaceous plants, etc.; while the animals include turtles, tortoises, crocodiles, tapir-like pachyderms, and certain birds with affinities to living tropical types. Associated with these are many forms of molluscan life which have their nearest living representatives in warm latitudes, such as cones, cowries, volutes, nautilus, etc., together with sword-fish, saw-fish, sharks, and rays. All this is good evidence that a warm climate prevailed during the deposition of the London Clay. The land was clothed with a tropical or subtropical vegetation, while analogous types of animal-life haunted the rivers and flourished in the sea of the period.

In the older geological systems we may say that all the species and nearly all the genera are extinct, so that any general resemblance which an assemblage of Palæozoic fossils may have to those of some particular groups of living plants and animals may have no climatic significance whatsoever. We may feel sure, indeed, that the abundant flora of the

Carboniferous period could not have flourished under arctic or even cold temperate conditions of climate; and we may be equally convinced that the abundant corals and cephalopods of Palæozoic times, with their numerous congeners, were not denizens of cold seas. Existing conditions might even lead us to believe that the massive limestones of those early ages were most likely formed in genial waters. For at the present day it is in warm seas that lime-secreting organisms, such as corals, pelagic molluscs, and foraminifera, flourish most abundantly, and are there giving rise to widespread and thick accumulations of calcareous matter. But whether the climatic conditions of Palæozoic times were similar to those of our present warm latitudes, it would be rash to conclude.

When the geographical distribution of Palæozoic floras and faunas, however, is kept in view, we may advance our inferences a step further. Should the fossils or groups of fossils of some particular formation be known to occur over vast areas of the earth's surface, in arctic, temperate, sub-tropical, and tropical latitudes, and even in similar latitudes of the Southern Hemisphere, we should be justified in the inference that the climatic conditions indicated by the fossils in question must have been singularly equable. The mere fact that in the earlier stages of the world's history, cosmopolitan forms of plant- and animal-life abounded, affords good ground for believing that the climatic conditions of those far past times differed considerably from the present. The climate of the globe in those days could not have been differentiated into such distinct zones as is now the case.

Geographical Conditions deduced from Fossils.—Fossils naturally yield evidence as to terrestrial, freshwater, and marine conditions.

(a) *Land-surfaces.*—These are seldom preserved. Nevertheless, they do occur in strata belonging to widely separated periods. Now and again, for example, the stools and roots of trees penetrating ancient soils, occur interbedded with sedimentary strata, a good example being furnished by the "dirt-bed" of Portland. This dirt-bed is simply an old soil containing the roots and stumps of extinct forms of cycads and conifers. It is intercalated between beds of freshwater origin, a succession which shows that, after the deposition of a wide area of fluviatile mud, dry land prevailed and eventually became covered with forests. Subsequently, owing probably to subsidence, the forest was submerged and buried under newer accumulations of fluviatile mud and silt. Many of the coal-seams of the Carboniferous period, with their underclays, tell a similar tale, and the same history is repeated by not a few of the lignites belonging to later geological periods. [Many coals and lignites, however, appear to represent masses of vegetable matter which have probably been drifted from the land into estuaries and shallow bays of the sea.] The not infrequent occurrence of arachnids, insects, lizards, and land-snails associated with beds of coal and lignite, is additional evidence of terrestrial conditions. Amber, again, is an abundant product of the lignite-bearing beds of Germany, and unquestionably represents the gum and resin which exuded from some of the forest trees of Tertiary times.

(b) *Lacustrine conditions.*—These are indicated by the presence of numerous freshwater molluscs and small crustaceans which are sometimes so abundant as to form beds of marl and limestone. Plant-remains, insects, and other relics of land-life, such as reptiles or mammals, often occur in lacustrine deposits. It is from lacustrine and estuarine deposits, indeed, that we obtain our fullest information as to the life of former land-surfaces.

(c) *Marine conditions.*—Relatively deep or, at least, clear water is indicated by thick masses of limestone, more or less abundantly charged with corals, sea-lilies, and other marine organisms. This inference is based partly on the fact that these limestones are comparatively pure—that is, they contain relatively little insoluble matter, and this is usually in a very finely divided state. In short, it is evident that such limestones have accumulated over parts of the sea-floor not reached by ordinary sediment—conditions which, as a rule, can obtain only at a considerable distance from the shore, and often, therefore, in somewhat deep water. Further, we judge from the analogy of the present, that, as existing corals only flourish in clear water, their predecessors probably demanded similar conditions. This inference is further strengthened by the fact that when, towards the top of a bed of limestone, the rock becomes more and more impure, the corals, and certain of their congeners, often begin to diminish in size, and even to become somewhat distorted, as if the influx of muddy sediment had acted prejudicially upon their growth and development.

Shallow-water conditions and proximity of the land are often evidenced by trails, burrows, and castings of annelids, tracks of crustaceans, etc., footprints of reptiles, amphibians, birds, or mammals. Along with these the strata may yield more or less well-preserved plants, insect-remains, and other relics of land-life. Beds containing such fossils are not infrequently estuarine deposits, and often exhibit ripple-marks, rain-prints, and sun-cracks.

Terrestrial Movements deduced from Fossils.—The presence of marine fossils in a rock obviously indicates oscillations of the sea-level. The appearance, for example, in our maritime districts, at various heights above the present sea-level, of terraces of sand and gravel, crowded with sea-shells of still living species, is proof positive of some recent crustal movement—either the land has risen or the sea-floor has subsided. Again, the existence at various depths on the sea-bottom of peat overlying the stools of trees belonging to kinds that still flourish in these islands, is evidence sufficient of a recent subsidence of the land.

Geological Chronology and Fossils.—In many cases it is quite impossible to correlate the formations occurring in separate regions by means of lithological characters alone. Within limited areas these may be reliable, but strata begin to change in character as they extend in various directions. Limestones, for example, may become gradually more and more argillaceous until at last they merge into shales, while these last may in their turn eventually pass into or inter-osculate with sandstones. Now, unless such changes could be followed in continuous open section, we could not possibly be sure that certain given beds of limestone, shale, and sandstone were exactly contemporaneous—all laid down on one and the same sea-floor. These rocks are so dissimilar that, unless we actually traced the connecting passages, we could not tell how one was related to another. So far as lithological character is concerned, they might each have been formed at a different time. But if the separate sections of strata contained fossils having the same general facies—and especially if several species were common to the limestones, the shales, and the sandstones, we could no longer doubt that all these rocks were accumulations formed in one and the same sea. Fossils are thus of paramount importance in the correlation of strata.

In the attempt to determine the relative age of our fossiliferous strata, the most important step was taken when William Smith, the father of Stratigraphical Geology, determined the sequence of the Mesozoic strata of England, and ascertained that each subdivision of that great series of rocks was characterised by the presence of certain particular types of fossils. Following his lead, geologists have since established the stratigraphical succession of fossiliferous strata throughout the major portion of the world. It is now recognised that every well-defined formation is marked by the presence of a particular flora or fauna, or by certain genera and species which are restricted to it. The presence of these *type-fossils*, as they are termed, enables the geologist at once to assign the rocks in which they occur to some definite horizon or stage in the great succession of sedimentary accumulations.

It is obvious, therefore, that some knowledge of type-fossils must be of great use in Practical Geology. How greatly they help a geologist in his endeavour to work out a stratigraphical succession will be shown when the subject of geological surveying comes to be discussed.

CHAPTER VII

STRATIFICATION AND THE FORMATION OF ROCK-BEDS

Consolidation of Incoherent Accumulations. Lamination and Stratification. Extent and Termination of Beds. Contemporaneous Erosion. Grouping of Strata. Contemporaneity of Strongly Contrasted Strata. Diagonal Lamination and Stratification. Surface-markings.

TECTONIC or Structural Geology treats of the arrangement of rocks, or the mode of their occurrence. It deals, in short, with the architecture of the earth's crust. The study of rocks, Petrography, is concerned simply with the nature and origin of rocks as aggregates of mineral matter. For the purposes of geology, however, this is not sufficient—rocks must be studied not only in hand specimens, but as constituents of the earth's crust. The geologist must take note of the positions they occupy as rock-masses, and the relation which the various rock-masses bear to one another. It is only by such observations that the order of succession, or, in other words, the relative age of rock-masses, can be ascertained, and the particular conditions under which they were formed, and the various changes they have since undergone, can be determined. It is, therefore, hardly too much to say that our knowledge of the many revolutions which have affected the earth's surface—the ever-changing geographical conditions of the past—is largely based on the study of structural geology.

In discussing the important subject to which the following chapters are devoted, attention must be largely confined to a description of rock-structures; but it may be helpful to the student now and again to consider what such structures mean, and to show how they may be interpreted by reference to existing operations of nature.

The structural geology of derivative rocks is upon the whole simpler and more readily understood than that of eruptive and metamorphic rocks, and, therefore, we shall consider first the phenomena which are specially characteristic of aqueous or sedimentary deposits. As we shall learn in the sequel, however, many of the structures presently to be described are met with likewise among igneous, and some of them even among metamorphic, rocks.

Consolidation of Incoherent Accumulations.—By way of introduction to the present subject, a few remarks on the consolidation of rocks may not be out of place. Rocks, as we have learned, are not all equally compacted, and their state of solidification is no certain test of their relative age. It holds generally true, however, that the fragmental accumulations of early geological ages are more consolidated than those which have been formed in later times. We cannot doubt that conglomerates, sandstones, shales, limestones, tuffs, and volcanic agglomerates were formerly as loose and incoherent as any similar masses now in course of formation. There is one obvious way in which some of these accumulations have become hardened, and we can see the process in operation at the present day. Water percolating through loose sand and gravel introduces mineral matter which, as the water evaporates, is deposited between the grains and pebbles, and thus binds these together. Frequently a sediment becomes compacted by the chemical action of water upon its own constituents. Calcareous accumulations, for example, tend to become consolidated by the solution of the calcium-carbonate, and its subsequent precipitation in pores and interstices; what were formerly yielding incoherent masses becoming in this way converted into hard rocks, such as calcareous sandstones, grits, and limestones. We know also that loose or soft materials may be compacted by the weight of overlying masses. Peat, for example, taken from the bottom of a bog, some twenty or thirty feet in depth, is often so compacted that when dried it resembles lignite. In like manner, thick artificial accumulations of loose rock-rubbish, as everyone knows, become in time sufficiently consolidated to serve as foundations for buildings. When we are assured, therefore, that many rocks of sedimentary origin, now visible at the surface, were formerly overlaid by hundreds or even thousands of feet of younger strata which have since been removed by the gradual process of denudation, we cannot doubt that the mere weight of such enormous masses must have tended to consolidate the beds upon which they rested. Once more, we note that heat tends to solidify deposits, as may be seen in the case of strata which have been baked and hardened by intrusions of formerly molten matter—eruptive masses. More potent and widespread, however, must have been the action of the internal heat of the globe upon thick accumulations of sediment deposited during long-continued subsidence of the sea-floor. Certain consecutive series of strata attain a thickness of 15,000 or 20,000 feet and more. It is obvious, therefore, that while the upper members of such series were being accumulated, the lower members must have been more or less affected by the rise of the isogeotherms or lines of equal subterranean temperature. According to what is known of the increment of heat downwards, a very high temperature must obtain at depths of 15,000 or 20,000 feet from the surface—certainly much in excess of the boiling-point of water. Strata brought in this way under the influence of the internal heat of the globe could hardly escape some degree of change. Not only would they be compressed by the superincumbent masses, but if interstitial water were present, chemical reactions amongst the various rock-constituents might often be greatly stimulated—water acting as a more powerful agent under increased heat and pressure. It can hardly be doubted that such must have been among the chief causes of the consolidation of ancient sedimentary accumulations.

Pressure may be brought about, however, by other means than the mere weight of overlying masses. The earth is a cooling body, and as the crust sinks down upon the slowly contracting nucleus, it necessarily becomes subject to enormous lateral compression. To this it can only yield by folding and crumpling up, and thus the rocks of which it is composed are frequently more or less highly disturbed. Strata which originally occupied approximately horizontal positions are now flexed, bent, and inclined at all angles, and such highly disturbed rocks, no matter what their geological age may be, are invariably much compacted, and sometimes so altered as to become truly crystalline and schistose. On the other hand, strata which have not been disturbed, but still retain their original horizontal position, are usually much less hardened, and rarely show any trace of metamorphism. The older Palæozoic rocks of this country, for example, are usually highly flexed and folded, and not only much compressed and hardened, but frequently rendered crystalline and schistose. In Central Russia, on the other hand, strata of the same age have retained their original horizontal position, and are so unaltered in general aspect as to resemble the sedimentary accumulations of comparatively recent times. The contrast between the undisturbed and more or less incoherent Eocene deposits of the London Basin and their much flexed and folded representatives in the Alps of Switzerland, is not less striking. Many similar contrasts might be cited, but it is enough to emphasise the fact that great crustal deformation is invariably accompanied by the induration of the rocks affected, no matter what their age may be. We may conclude, therefore, that the pressure induced by crustal movements has been one of the most effectual and widely acting causes of rock-consolidation.

Lamination and Stratification.—The most abundant and widely distributed rocks of derivative origin are undoubtedly the sedimentary types, conglomerate, sandstone, and shale. They have been spread out by the sorting action of water, and consequently occur in sheet-like form. Coarse gravel (*conglomerate*) has obviously been deposited upon beaches, or in shallow water at the mouths of rapid torrents, streams, and rivers. It may therefore be fluviatile, lacustrine, estuarine, or marine. In like manner sand (*sandstone*) and argillaceous sediments (*clay*, *shale*, etc.) are of both marine and freshwater origin. Sometimes a sedimentary rock has been deposited more or less rapidly; in other cases the process of sedimentation has been gradual and protracted. In the latter case, this is shown by the structure of the sheet-like deposit, which is usually composed of successive layers or very thin laminæ. In a deposit more rapidly accumulated, this structure is either inconspicuous or wanting.

Lamination is typically represented by the finer grained sediments, such as argillaceous shales. The laminæ of such deposits vary in thickness from an inch or so down to the finest films, not thicker than ordinary writing-paper (see Fig. 4). As a rule they cohere only slightly, so that a rock of the kind is more or less readily separated along the planes of lamination. Not infrequently, however, the laminæ have, owing to pressure, become more adherent. The laminated structure being the result of successive depositions of fine sediment by periodical river-floods, or by tidal or other marine currents, usually indicates accumulation in quiet water. These conditions are met with in lakes and estuaries, and over such areas of the sea-floor as are not much disturbed by currents—that is to say, in relatively deep water. Although lamination is very characteristic of argillaceous rocks, it is by no means confined to these. Laminated sandstones are of common occurrence, particularly when the rock is very fine-grained and more or less argillaceous. In coarser grained sandstones the individual laminæ are thicker than in argillaceous shales. When they exceed an inch or so, however, they are often described as *layers*.

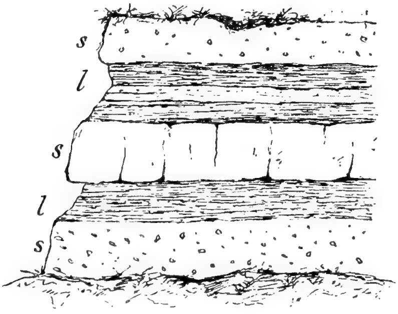


Fig. 4.—Stratification and Lamination.
s, *s*, *s*, non-laminated beds; *l*, *l*, laminated beds.

Bed or *Stratum* is the term applied to any sheet-like mass which has a more or less definite petrographical character, and is separated by well-marked parallel division-planes from overlying and underlying rocks. A bed may be homogeneous and without any apparent arrangement of its constituents, or it may consist of successive layers or laminæ. It is well to point out, however, that the terms "bed" or "stratum" and "layer" are purely relative. A sandstone consisting of a series of layers, for example, is often described as a *thin-bedded* rock. Again, a thin sheet of limestone, ironstone, or coal, intercalated in a series of shales, might be termed either a bed, a layer, or a seam.

The time required for the formation of any given thickness of sedimentary materials is necessarily indeterminate. Generally speaking, however, a bed of conglomerate may have been amassed more rapidly than an equal thickness of sandstone, and a sheet of sandstone may have been deposited in a shorter time than one of shale of equivalent extent and thickness. It is clear, however, that the rate of deposition of any particular kind of sediment must vary indefinitely. Certain sandstones, for example, may have been formed more rapidly than others of precisely the same character. Usually, however, where the rate of accumulation has varied in any marked degree, some evidence of this will be visible in the structure of the rocks. Thus, we may reasonably infer that a homogeneous sandstone, such as freestone or liver-rock, has been formed in less time than an equal mass of laminated sandstone. The liver-rock indicates continuous sedimentation, while the laminated sandstone points to a process of intermittent sedimentation. So, again, a structureless clay or loam has probably been accumulated more continuously, and therefore more rapidly, than a well-laminated shale. Nevertheless, it must be admitted that, in comparing separate beds of similar character and thickness, we can never be sure that an equal time was required for their deposition. Nay, even in the case of beds having the same composition and structure, and differing only in thickness, it cannot always be assumed that the thickest beds took the longest time for their accumulation. Probably, in most cases, they did, but many facts conspire to show that mere thickness is no sure test of the relative age of individual beds. If this be true of strata having the same character throughout, it is certainly not less true of beds which differ in composition and structure. A series of limestones and shales, one hundred feet in thickness, for example, may well have required for its formation a far longer time than a succession of several thousand feet of sandstones.

Intervals indicated by Planes of Lamination and Stratification.—The parallel division-planes separating individual strata are always more pronounced than planes of lamination, *i.e.* the planes separating individual layers or laminæ. This naturally suggests that a longer time has elapsed between the accumulation of successive strata than between the deposition of successive laminæ or layers. The length of interval represented by planes of stratification, however, is indeterminate. It may be quite short or very prolonged. In the case of shallow-water sediments, which are apt to show rapid alternations of coarser and finer grained deposits, no long intervals need have separated the deposition of the several kinds of sediment from each other. Rapid alternations of sediment are quite characteristic of alluvial, estuarine, and littoral or shore-accumulations. On the other hand, sediments accumulated in deeper water seldom show such rapid changes of character. They are usually fine-grained and persistent over wide areas. It is justifiable, therefore, to infer that planes of stratification amongst such accumulations will represent longer intervals than in the case of estuarine and littoral deposits. Should a pure marine limestone of some thickness, for example, be immediately underlaid and overlaid by thick argillaceous shales, as in the accompanying illustration (Fig. 5), we should be justified in assuming that the planes of stratification indicated lengthy intervals of time. Such an alternation of deposits would necessarily imply certain geographical changes, and these, as a rule, are only developed very slowly. We should infer that some change of conditions had arrested the deposition of muddy sediment represented by the lower beds of shale (sh^1)—either the source of supply was cut off, or the current which brought the sediment had lost its force, or was diverted in some other direction. The presence of thick pure limestone (l), consisting of the débris of corals and other marine organisms, points to a long-continued period during which the water remained clear. Then the sudden appearance of the overlying shales indicates a resumption of the conditions which obtained during the deposition of the lower shales. Possibly the alternation of beds may point to crustal movements. It may be that the floor of the sea subsided so as to carry it beyond the reach of mud-transporting currents, and after a prolonged period of rest, during which the corals and their congeners flourished, a new crustal movement in the opposite direction brought the same region again within the influence of currents laden with fine sediment. Explain the alternation of strata as we may, it is obvious that the planes of stratification in this case indicate more or less prolonged intervals. Geologists do not doubt that in some cases these planes may well represent a longer period of time than was required for the accumulation of the various strata which they separate.

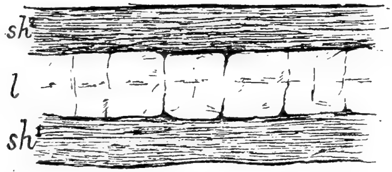


Fig. 5.—Shales and Limestone.

sh^1, sh^2, shales; l, limestone.

Extent and Termination of Beds.—Fine-grained deposits usually have a wider extension than coarse-grained accumulations. This is quite in keeping with what we know of the distribution of sediments in the lakes and seas of our own day. When a river enters a lake or estuary, the force of the current is immediately checked, and the heavier and coarser materials, gravel, etc., are at once thrown down. Grit and sand are swept out to a greater distance, and more extensively distributed, while the finest particles travel further still, and are spread over a yet wider area. Practically the same kind of sifting-out of sediments is effected by waves and tidal currents along an open coast-line. Banks of shingle and gravel accumulate close inshore, while grit and sand are carried further off, and the lightest or most readily transported sediment further still, the finer deposits invariably extending over the widest tract of sea-floor. Beds of shale, therefore, will generally have a greater lateral extension than beds of sandstone, grit, and conglomerate occurring in the same series of strata. Marine limestones, even when thin, often range over a very wide area. For their formation somewhat clear water is required, and, unless they be of the nature of coral-reefs, they will usually have accumulated at some distance from any land, and consequently often in relatively deep water. Under such conditions, therefore, we might have expected them to have a wide extension. All this is in keeping with the broad fact that accumulation of sediments proceeds with least interruption over those parts of the sea-floor which are not strongly swept by currents. Where there is much stir in the waters deposition of sediment is frequently interrupted, the sediments are coarse-grained, and show constant alternations of gravel, grit, and coarse sand. Where the sea-floor is not so liable to the scouring action of tidal currents, finer sand is spread far and wide, and passes out, as greater depths are reached, into mud and silt, which extend over still wider tracts of undisturbed sea-floor. At last a zone is approached, beyond which little or no terrigenous material is carried. Here the most important oceanic accumulations are of organic origin, calcareous and siliceous oozes[1] (see Fig. 6).

FIG. 6.—DISTRIBUTION OF MARINE ACCUMULATIONS.
s, gravel and sand; *c*, clay, mud, etc.; *o*, organic accumulations.

Each particular stratum in a sedimentary series may be looked upon as a lenticular sheet, which, seen in section, begins at zero, thickens out regularly or irregularly as the case may be, until it reaches its maximum development, and then thins off in the same way. This lenticular structure can often be seen in one and the same quarry, where the whole group of beds may consist of a series of short, imbricating, overlapping, and interosculating lenticular sheets. Thicker and more continuous strata of sedimentary origin behave in precisely the same way, the beds of coarsest materials thickening out and thinning off more rapidly than the fine-grained deposits. Such being the manner in which strata are arranged, it is obvious that sections taken across the same series of strata at different places will not often show the same number of beds, or if all be present, they will probably vary in thickness. In the following section (Fig. 7), for example, we have from *a* to *d* an apparently consecutive series of beds, and there is nothing at that end of the section to show that the several separating planes of stratification do not represent similar intervals. Yet we see that one plane (*x*, *x*) really indicates a longer interruption or pause in the process of sedimentation than the others, a pause of sufficient duration to permit of the accumulation of the beds bracketed at *z*.

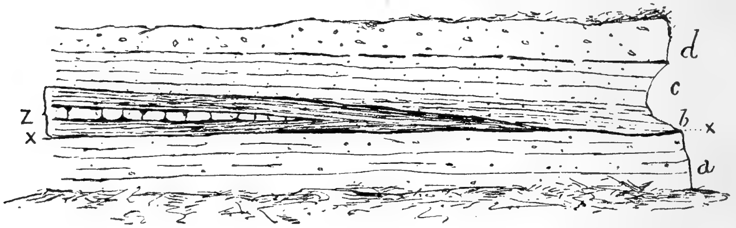
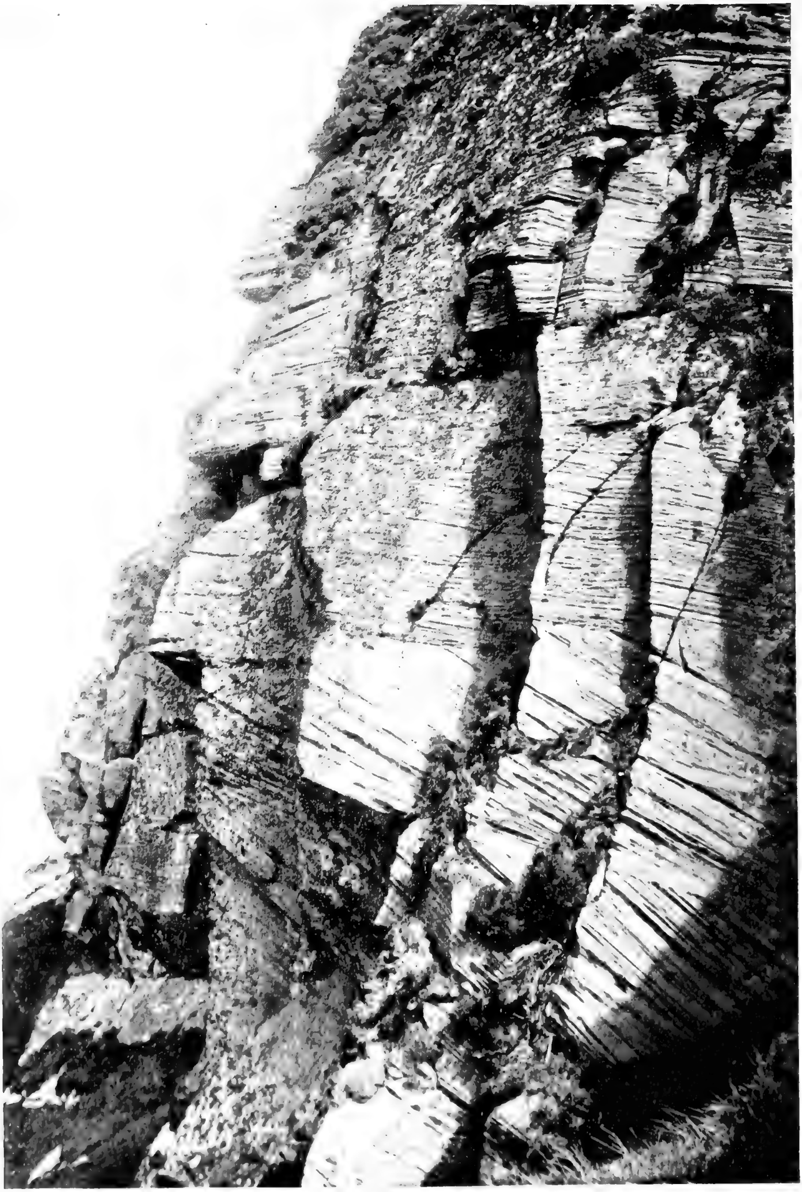


FIG. 7.—THINNING-OUT OF STRATA.

Contemporaneous Erosion.—The accumulation of relatively shallow-water deposits rarely goes on without interruption, for the currents which transport and lay down sediment not infrequently vary this action by scouring it out again and retransporting it elsewhere. Thus, during the formation of lacustrine, estuarine, and littoral and sublittoral deposits, accumulation and erosion often alternate. In the accompanying section (see Fig. 8) we have a series of beds, the accumulation of which has obviously been arrested at intervals. The bottom stratum, consisting of sandy clay (*c*), points to deposition in relatively quiet water. After such conditions had obtained for some time, the accumulation of fine sediment suddenly ceased, and the area of deposition was traversed by a stronger current which trenched and furrowed the stratum of sandy clay. As the force of this current declined, sand (*s*) began to be distributed over the denuded surface of the clay, and eventually attained a considerable thickness. Eventually, however, the speed of the current once more



Diagonal Bedding in Sandstone, Maol Donn, Arran.

From H.M. Geological Survey's Memoir, "The Geology of North Arran, etc."

[*To face page* 113.

increased, sedimentation was again locally arrested, and the process of erosion repeated, the sand being in its turn trenched and furrowed, and subsequently covered by arenaceous clay (c^1), just as this latter became denuded and afterwards overlaid by grit and sand (s^1).

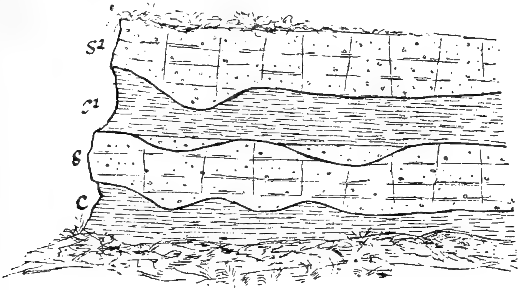


FIG. 8.—CONTEMPORANEOUS EROSION.

c, c^1, sandy clay; s, s^1, sandstone, grit, etc.

Grouping of Strata.—Although almost any diversity of strata may be seen in one and the same vertical section, yet, as might have been expected, it is usual to meet with rocks of similar character associated together. Thus, conglomerate is more frequently interstratified with grit and sandstone, than with fine argillaceous deposits, while limestone is associated rather with the latter than with coarser grained accumulations. Alternations of different kinds of sediment are quite characteristic of the deposits now forming in lakes, estuaries, etc., but usually the passage is from gravel to grit and sand, and not directly from shingle and gravel to silt and clay. Even in the case already mentioned (see Fig. 5), of a limestone intercalated between underlying and overlying shales, the change from the one to the other is not always so abrupt as it may seem to be. Not infrequently it will be found that the lower shales become more and more calcareous towards the top of the stratum, and that the limestone, in like manner, becomes gradually more and more argillaceous above—so that there is a sort of passage, as it were, from the one kind of rock into the other.

In the silting up of lakes and estuaries, however, it must happen now and again that coarse sediments are laid down directly on the surface of fine accumulations. As a rapidly flowing river pushes its delta outwards, the water naturally shallows in front of the advancing alluvial cone—in other words, the zone of gravel encroaches upon the area over which sand was formerly distributed, while the sand in its turn is laid down upon the finer mud and silt. Conversely, when sedimentation takes place over a gradually subsiding area, finer grained deposits continue to advance shorewards and extend over the surface of coarser accumulations. In general, however, such changes are only developed gradually, so that the passage from one kind of sediment to another (either in a horizontal or a vertical direction), will not usually be abrupt. But in the case both of an advancing delta and a retreating coast-line, sudden changes in the character of the deposits must occasionally take place. During floods and freshets, for example, the coarser detritus hurried forward by a river will make an abnormal advance, just as tidal currents will now and again sweep fine-grained sediment further inshore than usual. Sudden changes like this are often accompanied by the process already described as "contemporaneous erosion."

Contemporaneity of Strongly-contrasted Strata.—When we consider that sedimentary deposits are in process of formation over enormous stretches of sea-floor, in shallow and deep water alike, it is obvious that the most diverse accumulations may yet be of contemporaneous origin. It is no more than we might expect, therefore, to find that such rocks as grit and sandstone have been formed on the same sea-floor as limestone. When a series of strata is traced across a wide area, we constantly see some of the beds thinning off, and their position in the sequence being occupied by others of a different kind. In this way a great succession of thick-bedded limestones may be split up, as it were, by the intercalation of shales and sandstones, which continuously increase in thickness, while the limestones at the same time gradually get thinner and thinner until at last they disappear, and the whole series of strata then comes to consist of sandstones and shales alone. Similar changes are brought about by variations in the character of the individual beds themselves. Conglomerate, as we have seen, gradually shades off into pebbly grit and sandstone, just as siliceous sandstones pass laterally into fine-grained argillaceous sandstones, and these in their turn eventually merge into shales. So limestone tends to become mixed with clay or sand, and to shade off into calcareous shales or sandstones. Again, coal and ironstone may mutually replace each other; or each may lose its own distinctive character and gradually pass into carbonaceous or ferruginous shale.

An example of a well-marked group of strata which gradually changes its character as it extends from one region to another is supplied by the Lower Oölite of England. This formation may be followed from Somerset through Gloucester and the Midlands to the Humber. Throughout its whole course it rests upon and is covered by well-defined argillaceous beds—the Lias below and the Oxford Clay above. In the south of England the formation is composed essentially of limestones. Followed to the north, however, it becomes more and more arenaceous and argillaceous, until in Yorkshire the limestones of the southern district are entirely replaced and represented by ordinary sandstones and shales with associated coals and ironstones. The transformation of the deposits is not hard to understand. The calcareous accumulations of the south are obviously marine, while the arenaceous and argillaceous deposits of the north are of estuarine and brackish water origin.

A somewhat similar change comes over the great Carboniferous Limestone formation when it is followed from England into Scotland. In the Mendip Hills the formation consists almost entirely of limestones, which reach a thickness of 3500 feet at least. In Northumberland, the limestone series of the south is represented by a great succession of sandstones and shales, with associated coal-seams and beds of limestone that vary individually in thickness from 7 feet to 150 feet—the entire formation ranging from 2500 feet to upwards of 6000 feet. In Scotland the arenaceous and argillaceous element acquires a very great development—probably not less than 10,000 feet. The only limestones present, however, are some half-dozen beds, varying in thickness from a few feet up to 20 or 30 yards, which, along with numerous seams of coal and ironstone, are intercalated in the upper part of the series.

Diagonal (Oblique or Cross-) Lamination and Stratification.—While it is generally true that sedimentary deposits are spread out in approximately horizontal sheets, now and again both laminæ and bedding show much irregularity—not only the individual beds, but the layers of which they are composed, being often inclined to each other at various angles. The structure is shown in Plate XXIV., and owes its origin to changes or oscillations in the direction and force of currents. Hence it is often termed "current-bedding" or "false-bedding," in reference to the fact that the bedding does not indicate that of the series of strata in which it occurs. The structure is common in littoral deposits and accumulations formed in shallow water, where there is much shifting and eddying of current-action. Not infrequently a highly false-bedded sandstone is directly underlaid and overlaid by evenly bedded strata, which give evidence of quiet and undisturbed sedimentation.

False-bedding of a pronounced character is characteristic of the deltas formed by torrential streams and rivers. Such deltas advance more or less rapidly, and usually present a somewhat steeply sloping front. As already explained, gravel and coarse detritus are shot forward by the current, and roll down this steep bank—the finer sediment being carried further and coming to rest on the bed of the lake or estuary, so as to form approximately horizontal accumulations. Thus in time, as the bank advances, steeply-inclined beds of gravel (*g*) come to overlie horizontal sheets of sand (*s*) and silt (*m*), (Fig. 9).

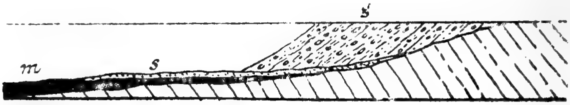
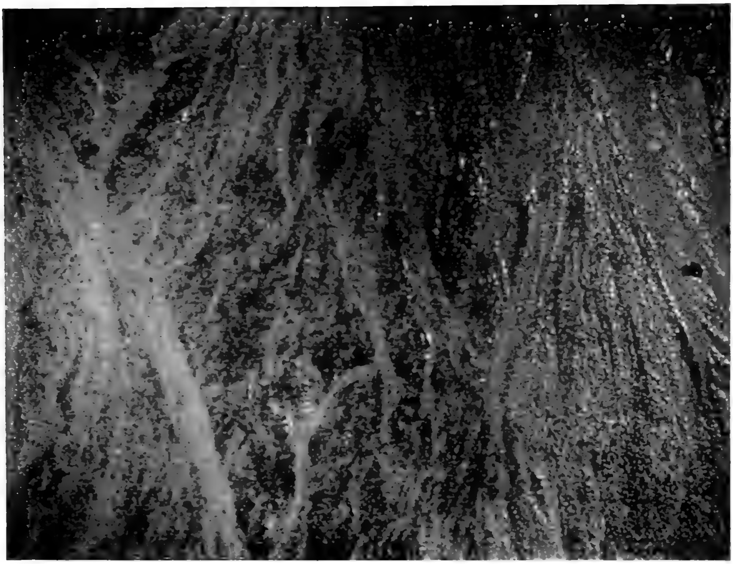


FIG. 9.—DELTA FORMED BY TORRENTIAL STREAM.
g, gravel; *s*, sand; *m*, silt.

Surface-Markings.—The surfaces of derivative rocks often exhibit interesting markings, among which the most notable are *current-marks*. These are of precisely the same character as the ripple-marks seen on modern sea-beaches (see Plate XXV. 2). In the shallow water of a sea-beach the ripple-marks slowly advance with the inflowing tide. They usually present a long, gentle slope seawards, and a short and more abrupt slope towards the shore. With the ebb-tide, the crests of the ridges tend to be smoothed off or truncated. When the movement of the water is irregular, as between skerries, boulders, etc., the result is the formation of numerous miniature hummocks and dimples, or straggling hollows and rounded ridges.

Although current-marks are most commonly associated with beach-deposits, they are not confined to these, but may originate at any depth to which the agitation of the water extends. They have been observed forming in clear water at depths of 50 feet and more. Ripple-marked surfaces are common in many sandstones and argillaceous beds, and often occur one over another throughout a thick series of strata. As each advancing tide



1. Rill-marks on Beach at Elie, Fife.

Photo by Dr Laurie.

2. Current-marks in Carboniferous Sandstone, Shore near St Monan's, Fife.

Photo by Dr Laurie.

[*To face page* 116.

effaces old marks, and replaces these by new ones, it is difficult to understand how, under ordinary conditions, a rippled surface of sand can be preserved. Hence it has been surmised that many of the ripple-marked surfaces which appear in rocks of all geological ages may have been produced below low tide-level, in shallow bays or in estuaries, where sedimentation is more or less continuously carried on; so that rippled surfaces might be often preserved by the gentle deposition upon them of fresh accumulations of sediment. However that may be, it seems certain that not infrequently ripple-marked surfaces have really been formed between high and low water. In some cases these have probably been preserved by the deposition over their surface of a thin film of clay. In other cases the rippled sand (often to some extent argillaceous) had become sufficiently consolidated to resist the action of the next incoming tide. It must be remembered, that at low tide on gently shelving shores a wide expanse of beach is laid bare. Exposed to the rays of a hot sun, the fine-grained sand or sandy mud might thus, over wide areas, be so dried and hardened as to resist the obliterating action of the flowing tide, and under such circumstances it is conceivable that surface after surface might be covered up and preserved. Again, on flat shores, wide belts of rippled sand and mud might be exposed between the lines of spring and neap tides. Hence, the surfaces above high-water of ordinary tides might become dried and consolidated before they were eventually covered by newer accumulations. The layer immediately overlying a ripple-marked surface usually shows a more or less perfect cast, which, when removed from its position, is often hard to distinguish from the actual mould or original surface. Frequently, however, the hollows are more sharply pronounced than the ridges, and when such is the case the cast of a hollow would show a sharp crest, such as could not be formed on the summit of a ridge.

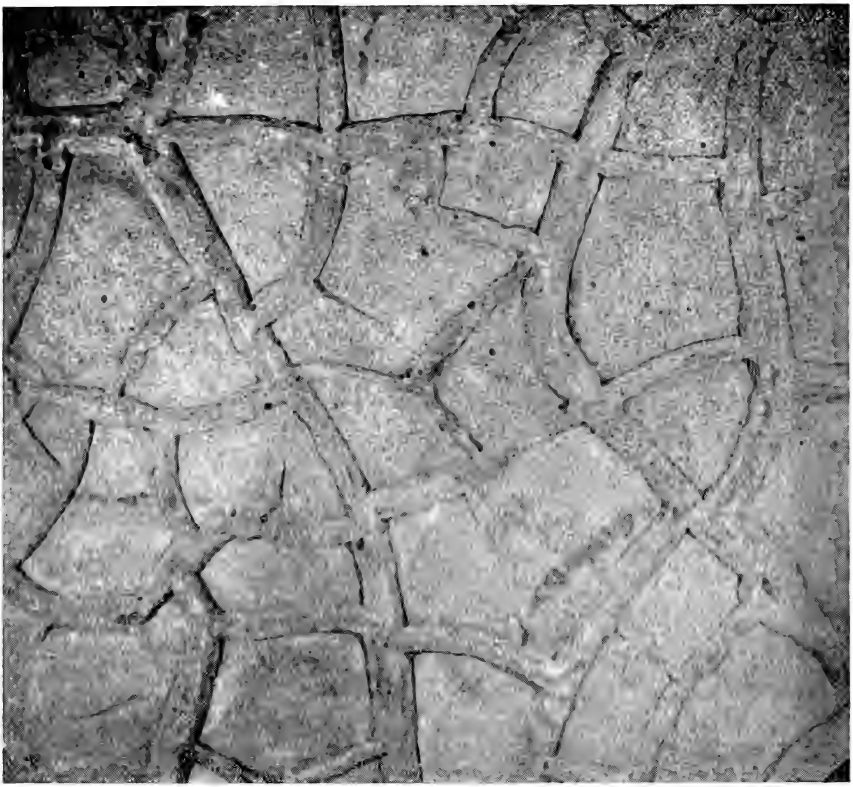
Wave-marks.—These are seen forming on modern sea-beaches during ebb-tide. They are delicate outlinings which mark the limits reached by the waves as they die out. If the edge of the thin layer of advancing water be observed, it will be seen that it sweeps along with it fine grains of sand, and more particularly particles which, by reason of their shape (mica-flakes) or light specific gravity, (coaly matter) are readily carried forward. When the wavelet dies out, these materials are stranded so as to form a miniature ridge, which is often rendered conspicuous by the presence of black carbonaceous matter. Wave-marks of this kind are not infrequently seen on the surfaces of fine-grained sandstones and flagstones, and are good evidence of a beach-formation.

Rill-marks (see Plate XXV. 1).—These are small furrows formed on a sandy or muddy beach by the trickling downwards of little rills during the retreat of the tide. They are occasionally visible on the surfaces of fine-grained sedimentary rocks. When they are numerous and run into each other, they often simulate the appearance of some kind of algæ, and have not infrequently been described as fossil sea-weeds.

Sun-cracks (Plate XXVI.).—Round the shores of inland seas and lakes, the level of which is liable to fall during the dry season of the year, a wide belt of gently shelving ground is laid bare. The same is the case in many river-valleys—broad flats appearing when the rivers are low. Frequently such exposed tracts consist of clay or mud, which, under the influence of the sun, becomes dry and shrinks, so that the surface cracks into polygonal cakes. When the wet season arrives, and the level of the water rises, sand may be deposited over the consolidated and fissured clay, and thus a cast of the cracks will be formed. The same action may take place on low, flat beaches which are exposed to a hot sun during the retreat of the tide. Sun-cracks are thus of common occurrence in many geological systems. The casts usually adhere to the overlying stratum, of which indeed they form a part.

Rain-prints.—In like manner the pits made by rain on the surface of fine-grained deposits have occasionally been preserved. The smooth bedding-planes of argillaceous sandstones, shales, and mudstones are not infrequently pitted in this way, the casts of the pits occurring on the under surface of the overlying stratum. Sometimes the direction of the wind at the time the rain fell is shown by the inclination of the pits in one particular direction. In such cases there is occasionally the appearance of a slight ridge on one side of the pits, as if some of the fine sediment had been flicked out by the drops as they fell.

Animal-tracks, etc.—Additional evidence of beach-conditions is obtained from tracks left by animals. Thus, tracks or trails of annelids, molluscs, crustaceans, etc., worm-burrows and castings, and the footprints of reptiles, amphibians, birds, and mammals, have been preserved, usually in fine-grained sedimentary strata. Now and again, also, certain puzzling impressions make their appearance, which have often been described as plant-marks. Possibly some of these may have



1. Cast of Sun-cracks in Sandstone. One-third natural size.

2. Another specimen. About half natural size.

[*To face page* 118.

been formed by sea-weeds waved to and fro by eddying waters, the fronds of the algæ brushing the surface of the sand or mud, and thus drawing or etching curved patterns. Others, again, may represent the trails made by floating algæ or by the tentacles of a jelly-fish. Various surface-markings which mimic organic structures and have been given generic and even specific names are probably often of mechanical origin, formed either during or after consolidation of the rocks in which they occur.

CHAPTER VIII

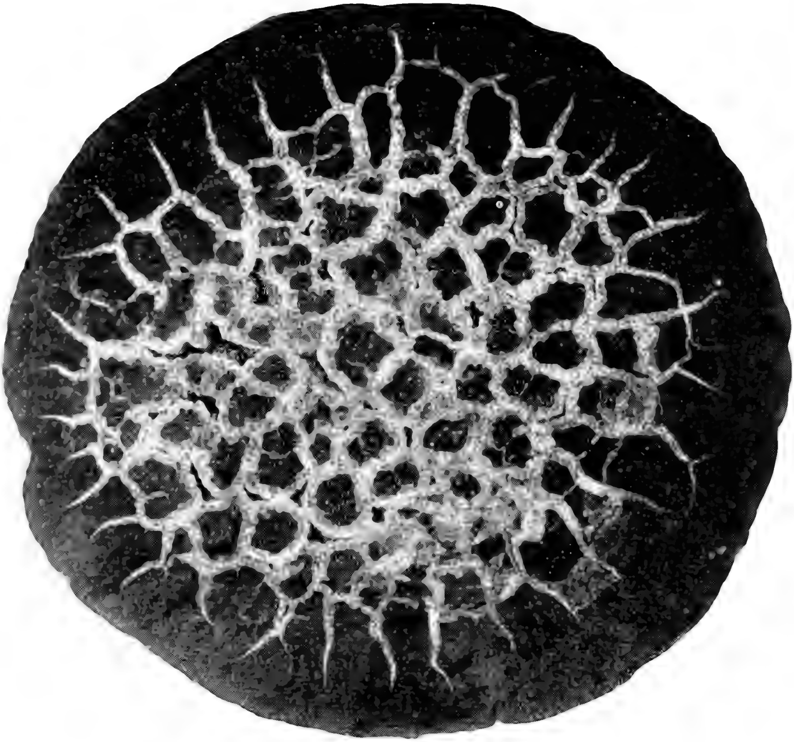
CONCRETIONARY AND SECRETIONARY STRUCTURES

Siliceous Concretions—Flint, Chert, Menilite. Calcareous and Ferruginous Concretions—Septaria, Composite Nodules, Rattle-stones, Fairy-stones, Kankar, etc. Clay-ironstone Nodules, Pyrite, Marcasite, Gypsum, Dendrites. Concretionary Sandstones, Argillaceous Rocks, and Limestones. Concretionary Tuffs. Concretions in Crystalline Igneous Rocks. Secretionary Structures — Amygdules, Geodes, Drusy Cavities.

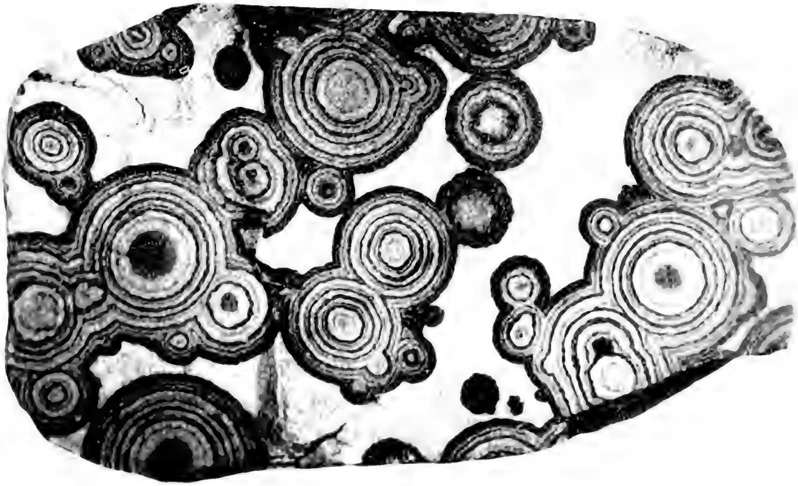
Concretionary Structures may occur in almost any kind of derivative rock. Sometimes they affect the mass of a rock; at other times they take the form of various sized spherical or lenticular bodies or *nodules*, scattered regularly or irregularly through a rock, or they may appear as more or less interrupted layers or vertical and ramifying veins, or as well-formed crystals. In most cases they owe their origin to the gradual aggregation of mineral matter originally diffused through the mass of the rock in which they occur. Occasionally, however, the mineral matter has been introduced from the outside by percolating water. The commonest concretions are siliceous, calcareous, and ferruginous, and there is a strong tendency in spherical concretions to assume internal radiating and concentric structures.

(*a*) SILICEOUS.—Among the most familiar examples of siliceous concretions are the *flints*, which occur so frequently in chalk. Flint nodules are usually irregular in form, and vary in size up to a foot or more in diameter. They are white externally, and brown to black internally. They often enclose or partially enclose fossils, more particularly sponges. Usually they are arranged in lines that coincide with the bedding-planes of the chalk. They may coalesce to form more or less interrupted sheets or seams of flint (some three or four inches thick), which follow the bedding of the chalk, or may traverse it, as irregular vertical or ramifying veins. In the older limestones *chert* plays much the same part as flint

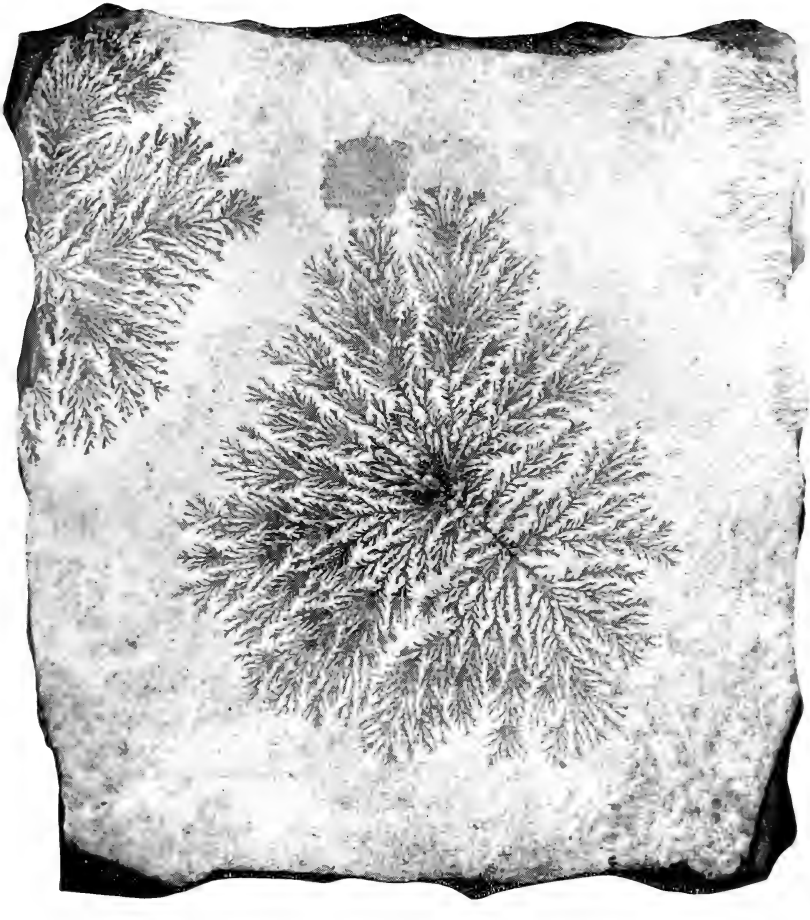
PLATE XXVII.



1. Section of Septarian Nodule (Clay-ironstone). About one-half natural size.



2. Section of Spherical Concretions (Ferruginous) in Sandstone. About one-half natural size.



Dendritic Markings (Psilomelane) on Limestone. Two-thirds natural size.

in chalk, and is probably, like the latter, in many cases of organic origin. Now and again, however, it may have been a deposition from thermal water. In such cases it occurs as thin laminæ, interleaved with similar laminæ of limestone—the layers being often highly puckered, crumpled, or confusedly contorted and involved, as if the deposits had been disturbed by the bubbling up of spring-water before they had become quite solidified. These appearances, however, may be otherwise accounted for. The siliceous solution may have been originally in a colloid or jelly-like condition, containing some percentage of water. Thus, when the mineral began to lose its water and solidify, the contraction of its bulk would give rise to much distortion and confusion—later accretions of silica filling up any fissures or cavities thus produced. Siliceous secretions are not uncommon in some argillaceous rocks: nodules and seams of chert (often radiolarian), for example, occasionally occur in Palæozoic shales, and reniform *menilite* appears now and again in marls of later age. Even sharp crystals of *quartz*, generally of small size, have occasionally been developed in marly clay.

(*b*) CALCAREOUS and FERRUGINOUS.—Spherical and nodular calcareous and ferruginous concretions are characteristic of many argillaceous rocks and of some sandstones. In laminated clay the mineral solutions have made their way most readily along the planes of sedimentation, so that the resulting concretions are usually somewhat lenticular, and often assume the shape of flattened spheroids. When numerous, they not infrequently coalesce so as to form irregular concretionary bands or layers. Very often, however, they are scattered sporadically through the beds in which they occur. In homogeneous clay-rocks, without apparent lamination, the concretions are usually either spherical or variously shaped, and often irregularly dispersed. Frequently they have formed round a nucleus, which may consist of mineral matter, but is more commonly of organic nature, such as a shell, a coprolite, a fish, a fragment of plant, etc. A concretion may be compact and homogeneous throughout, or may consist of concentric shells, or while externally compact it may be much cracked and fissured internally. The cracks are widest towards the centre of a concretion, and die out towards its circumference, as if the interior had contracted after the outside had dried and become consolidated. They are often partially or completely filled with subsequently introduced mineral matter, usually calcite. Concretions of this kind are known as *septaria* or *septarian nodules*, in allusion to the septation or partitioning of the interior (see Plate XXVII. 1). Septaria are commonly either calcareous or ferruginous. Occasionally, concretions consist of concentric shells of different chemical composition. In a nodule, composed for the most part of ferruginous matter, one or more of the shells may be calcareous; or the core or kernel may be calcareous, and the external shells ferruginous.* Owing to the subsequent action of percolating water, the calcareous portions may be completely

---

* Occasionally one or more of the concentric shells may consist of oxide of manganese (psilomelane).

removed in solution. In this way, by the removal of a calcareous layer from the interior of a nodule, a central ferruginous kernel becomes detached, and rattles when the concretion is shaken (*Klapperstein*, or Rattle-stone). When a calcareous core is entirely dissolved, a nodule, of course, becomes hollow. Many nodules, however, are rendered hollow, simply owing to the contraction of the interior after the outer shell has dried and hardened.

Concretions of the several kinds referred to in the preceding paragraph are all obviously of secondary origin—they are superinduced structures. This is shown by the fact that the planes of sedimentation can often be seen passing through them, and never curving over them, as would have been the case had they been loose stones and boulders covered up while lying on lake-floor or sea-bottom. Among familiar examples of concretionary calcareous nodules are the so-called *fairy-stones* so frequently met with in alluvial clays. In Germany they are common in loess, and are known to the country-folk as "Löss-püppchen, Löss-männchen," etc., and as "Marlekor" (Kobolds' playthings) or "Näkkebröd" (Nixies' bread) in Sweden. Similar calcareous concretionary nodules termed "kankar" are abundantly developed in many of the alluvial deposits of India. Reference may also be made to the curious calcareous concretionary structures which occur in the Tertiary sand of Fontainebleau, near Paris. These frequently take the form of single crystals of calcite, or of groups and aggregates of such rhombohedral crystals. Ferruginous concretions are well represented in this country by the balls and nodules of *clay-ironstone* (sphærosiderite) that occur so abundantly in the black shales of the Carboniferous System. They vary in size from a hazel-nut to flattened spheroids measuring two or three feet across, but these last are not common. Many contain a fossil at the centre, while others seem to consist wholly of inorganic materials. A large proportion, it may be added, are septarian. As calcareous and ferruginous concretions alike tend to be developed in the direction of the bedding-planes of the rock in which they occur, it frequently happens that contiguous nodules become fused together, so as to form more or less continuous seams of limestone or of ironstone, as the case may be. Sometimes such seams maintain an uniform thickness, but more usually they are lumpy, thickening and thinning irregularly. Concretions of disulphide of iron (*Pyrite* and *Marcasite*) are of frequent occurrence in sandstone, clay, chalk, and coal. They vary in size from minute grains up to nodules two or three inches in diameter. In the form of nodular concretions marcasite is much more common than pyrite, the concretions having usually an internal, fibrous, radiating structure. Now and again marcasite, however, assumes a crystalline form, as in the flat, spear-headed "twins" which are seen in the chalk deposits at Dover and Folkestone. Pyrite does not occur so commonly in nodules as marcasite, but has a much wider distribution in the crystalline form, crystals and crystalline aggregates appearing in many kinds of derivative rocks, either dispersed through a rock-mass or lining its minute cracks and fissures. As sporadic crystals or groups of crystals, it often appears in clay-slate, but such occurrences fall to be considered under the head of metamorphism. No hard-and-fast line can be drawn between the changes which produce concretions and concretionary structures in "unaltered" rocks, and those which have induced the aggregation and crystallisation of mineral matter in certain "altered" or "metamorphic" rocks.

Sulphate of lime is not so often met with in concretions as carbonate of lime and ferruginous compounds. In some clay-rocks, however, *gypsum* concretions are common enough. Sometimes these appear as large perfect crystals and twins of the mineral, but more frequently as lenticular nodules, or layers, an inch or more in thickness.

The oxides of manganese and iron occur not only in nodular forms, but frequently appear as thin films coating the surfaces of the natural division-planes of rocks, such as joints and bedding-planes. They usually assume delicate plumose or plant-like forms resembling sprigs of moss, etc., and hence are termed *dendrites* or *dendritic markings* (see Plate XXVIII.). Although usually appearing only on division-planes, now and again they ramify through the substance of fine-grained rocks, such as certain limestones, on sections of which the markings often simulate belts of trees, hedgerows, etc. (*landscape-marble*).

CONCRETIONARY ROCKS.—Not only do mineral solutions tend to form concretions of various kinds in rocks, but the rocks themselves have not infrequently acquired a concretionary structure. Some *sandstones*, for example, seem to be largely composed of aggregates of ball-like or larger spheroidal masses. Few sandstones, indeed, do not in places show some indications of this concretionary structure. The spheroids are now and again enclosed in dark brown ferruginous crusts, the rock within being often bleached, and it may even be reduced to the condition of loose sand. When sandstone of this character is exposed by quarrying, the freshly cut rock may show concentric bands of a dark brown or red colour, some of which may be an inch or less in width, while others may exceed several feet. The origin of the structure is obscure. The ferruginous matter may have been introduced by percolating water, but some of it at least has been abstracted from the sandstone itself. The concentric shells of ferruginous matter shown in Plate XXVII. 2 are not hard to explain, and their mode of formation may throw some light on that of the larger concretionary masses to which reference has just been made. They owe their origin undoubtedly to the presence of disseminated granules or crystals of some ferruginous mineral, almost certainly pyrite or marcasite. By the action of water soaking into the stone the mineral is broken up chemically, and a ferruginous solution formed, which spreads outwards as a drop of ink does on blotting-paper. Evaporation taking place around the outer margin of the solution, iron-oxide is precipitated, and the first ring or shell is formed. The process is repeated by the formation of a second shell inside the first, and thereafter the production of successive concentric shells is continued, each forming inside of its predecessor, until the ferruginous solution is exhausted. In some cases, a portion of the ferruginous mineral at the centre may remain, but it is usually so small and so much altered that its original character is hardly recognisable.

Other kinds of concretionary structures are frequently met with in sandstones. Small quantities of carbonate of lime or carbonate of iron, diffused through the rock, tend to aggregate so as to form irregular concretionary masses of sandstone, which are much harder than the surrounding rock. Cracks and crevices in concretionary masses of this kind are often filled or lined with crystalline siderite or calcite, as the case may be. The hardened rock (known as "kingle" in Scotland) breaks with a splintery fracture, and is rejected by the quarrymen as unsuitable for building purposes.

Argillaceous rocks hardly less frequently assume concretionary forms. Now and again a whole bed of shale may exhibit the structure—the rock appearing to be composed of an aggregate of various sized spheroids. The spheroids usually show a concentric arrangement—the concentric shells being in some cases separated from each other by thin films of ferruginous matter.

Calcareous rocks often enough acquire a concretionary structure—the most pronounced examples of the kind being furnished by dolomitic or magnesian limestone, as already described (p. 65). Reference may also be made to the oölitic structure of certain limestones, calcareous tufas, and ironstones, which, however, in most cases is original (see p. 70).

Concretionary structures, comparable to those that characterise so many derivative rocks, can hardly be said to occur in igneous rocks. Exception, however, must be made of the *tuffs*, in many of which concretionary ferruginous and calcareous nodules occur, while now and again tuff itself may exhibit concretionary structure, such as that seen occasionally in argillaceous shales. But the concretionary structures that affect many crystalline igneous rocks differ from those which occur in derivative rocks in being original and not superinduced. For example, the dark, irregular shaped aggregates of ferromagnesian minerals which appear in many granites, gabbros, and other plutonic masses, and the sporadic nodular masses of olivine so frequently met with in basalt, are early segregations from the original molten magma. They are not, like the septarian nodules described above, younger than the rocks in which they occur. So, again, the aggregates of spherical bodies which constitute orbicular diorite or napoleonite are not superinduced but original structures—they consist of radially and concentrically arranged felspar and hornblende—the two primary and essential ingredients of the rock (see Plate XIV.). Similar original concretionary structures are met with in other crystalline igneous rocks, as, for example, the ball-granite ("Kugel-granit") of Finland.

Secretionary Structures.—These are especially characteristic of certain types of igneous rocks, but may occur in almost any kind of rock having a cellular or cavernous structure. They consist of mineral matter which has been deposited on the walls of cavities, usually in successive layers, and thus they may be said to increase from without inwards. In this respect they differ from concretions which owe their origin, as already explained, to the aggregation of mineral matter round a central point, so that they grow from within outwards. Secretions are typically represented by the mineral matter which so often occupies the vapour cavities of ancient lava-form rocks. As these cavities are usually somewhat flattened from having been drawn out in the direction of flow, the subsequently introduced secretions are often almond-shaped. Hence they are termed *amygdules*, and the rock itself is said to be *amygdaloidal.* Such cavities vary in size from mere pores up to hollows measuring many inches in diameter. Sometimes the walls are lined with a mere film of mineral matter; in other cases the cavities may be largely or completely filled up (see Plate I. 1). A secretion may consist of one and the same kind of mineral matter, or of successive bands of various minerals, and some of these bands may be distinctly crystalline, while others are crypto-crystalline or apparently amorphous. In other cases a cavity may be occupied by an irregular aggregate of different minerals—all more or less well crystallised. A hollow secretion, readily separable as a nodule from the rock in which it was formed, is termed a *geode;* while *druse* is the term applied to a cavity which is lined or studded with crystals. Nevertheless, "geode" and "druse" are sometimes used interchangeably. It is common, for example, to apply the term geode to siliceous secretions occurring in the form of hollow spheroids or balls, in such rocks as limestone and highly decomposed amygdaloids, from which the ball-like bodies are readily detached. "Geode," therefore, refers rather to the secretion than to the cavity in which it occurs. "Druse," on the other hand, has reference not only to a particular character of the secretion, but to the fact that it occupies a cavity. Hence, geologists often speak of *drusy cavities*, meaning by that simply crystal-lined hollow spaces.

The secretions occurring in crystalline igneous rocks may be (*a*) *original or synchronous*, or (*b*) *subsequent or superinduced.* As types of the former (*original*), may be cited the drusy cavities in granite (Plate X. 2), which are partially filled with well-crystallised examples of one or more of the original constituents of the rock. Obviously, such secretions must be synchronous with the formation of the granite. Analogous to the drusy cavities in granite are the mineral-lined or mineral-filled cavities of irregular shape which are characteristic of some acid igneous rocks (rhyolite). These, it can hardly be doubted, are deposits from heated solutions, formed before the rock in which they occur had cooled.* Probably of similar origin (at least in some cases) are the zeolites, which occur so abundantly in the vapour cavities of certain basic rocks, as, for example, the fine drusy cavities of the Tertiary basalts of the Færöe Islands and Iceland.

Among *subsequent* secretions, the most typical are the amygdules referred to above. While the formation of these may sometimes be almost synchronous with that of the rock in which they occur, there can be little doubt that in most cases the amygdules are of subsequent origin, the mineral matter having been introduced by percolating water long after the cellular rock had cooled and solidified. Amygdaloidal rocks are usually more or less decomposed, the amygdules consisting of material derived from the breaking up of one or more of the original rock-constituents, especially the felspars.

The minerals of most frequent occurrence in amygdaloidal cavities are calcite, chalcedony (agates), quartz, zeolites, green-earth, etc. As siliceous secretions are more durable than the igneous rocks in which they occur, they are often found in the soils and subsoils resulting from the decomposition of amygdaloidal rock, and under such conditions they are, as already indicated, often termed *geodes*.

---

* There can be little doubt that the mineral composition of igneous rocks has sometimes been greatly affected by such heated solutions. For example, the kaolin or china-clay worked in Cornwall consists simply of granite decomposed *in situ*. The decomposition is obviously due to the action of highly heated vapours coming from the more deeply seated and perhaps unconsolidated, or only partially consolidated, portion of the plutonic mass.

CHAPTER IX

INCLINATION AND CURVATURE OF STRATA

Dip—Apparent and True. Terminal Curvature. Outcrop influenced by Angle of Dip and Form of Ground. Strike. Curvature of Strata—Monoclinal Folds, Quaquaversal and Centroclinal Folds, Normal or Symmetrical Folds, Unsymmetrical Folds, Inversion, Recumbent Folds, Fan-shaped Structure, Contorted Strata, Origin of Folds.

IN considering the formation of rock-beds, some incidental reference was made to the fact that strata, which must originally have been horizontally disposed, are now frequently inclined, and even flexed, folded, and contorted. These and other superinduced structures now fall to be described in more or less detail.

Dip.—The *dip* is the inclination of beds down into the earth, and is measured in degrees by the angle between the plane of the strata and the plane of the horizon. The instrument employed for this purpose is called a *clinometer*—a graduated arc with pendulum. For general use it is convenient to have the clinometer combined with a *compass*—with the latter one takes the *direction*, and with the former the *degree* or amount of dip.* When strata are so exposed that the line of greatest inclination can be observed, the direction and amount of dip are readily ascertained. If the surface of an exposed bed be smooth and even we have only to place the clinometer upon it, taking care that the edge of the instrument is arranged in the direction of greatest slope (*i.e.* the direction in which water would flow if poured upon the surface), and that the pendulum is swinging freely. The pendulum points, of course, to the degree or amount of dip. If the surface be not very smooth, one may lay one's hammer or walking-stick upon the rock in the line of dip, and thus provide a longer

* *See* Appendix E.

edge on which to place the clinometer—the object being, of course, to get as true an average as possible for the whole surface. But to insure this, it is always advisable to check the result thus obtained by taking the angle of dip at a little distance from the section exposed. To do so, the observer, standing back from the section, holds the clinometer within a short distance of his eye, and in such a position that the straight edge of the instrument shall coincide with the lines of the dipping strata. The distance at which one should make an observation of this kind will depend largely on the height of the exposed section. If the height be only a few yards the dip may be measured at no greater distance than the height. But if the section be much higher the observer must stand proportionally further back—the object being to make the edge of the clinometer coincide with as long a stretch of the lines of bedding as possible. In this way we usually get, by means of one observation, a more reliable average than we should if we had taken the average of twenty observations made by placing the clinometer directly on the rock-surface. Even in the case of false-bedded strata, it is often possible, by standing well back from the section, to get a good average dip for the whole series. But when the actual surfaces of the bedding-planes are not visible, the beginner may easily be deceived as to the true position of the strata. The lines of bedding which are seen traversing the face of a cliff do not necessarily indicate the true direction and amount of dip. Beds that are really inclined may even appear to be horizontal. In the accompanying

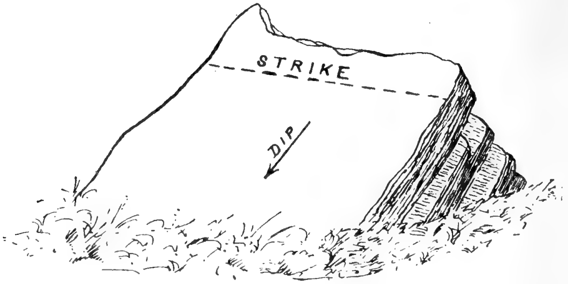


FIG. 10.—DIP AND STRIKE OF STRATA.

PLATE XXIX.

ANTICLINAL FOLD IN LIMESTONE, PENTON BRIDGE, LIDDEL WATER, DUMFRIESSHIRE.

Photo by H.M. Geological Survey.

[*To face page* 128.

Contorted Shales and Hard Bands (Greywacké), Ardwell, near Girvan, Ayrshire.

Photo by H.M. Geological Survey.

section, for example (Fig. 11), the beds at *a* seem to be horizontal, when in reality they dip at a considerable angle, as shown at *b*—where the cliff runs in the direction of the true dip—the direction and amount of which can therefore be readily determined. Not infrequently, however, cliffs and other cuttings or sections traverse the dip of the strata obliquely, and when such is the case, the apparent dip shown by the edges of the exposed beds does not indicate either the exact direction or the full amount of the true dip, which is always greater than that of the *apparent* dip. When the observer suspects that the inclinations exposed in two adjacent sections are only apparent dips, he may yet find the true direction by the geometrical method referred to in Appendix C. As a rule, however, an apparent dip can rarely, if ever, deceive one who is not content to view sections from a distance. Close examination will rarely fail to discover on even the smoothest of cliff-faces, irregularities—ledges, depressions, entering and re-entering angles, etc.—in one or other of which the upper or under surfaces of the bedding-planes are almost sure to be disclosed.

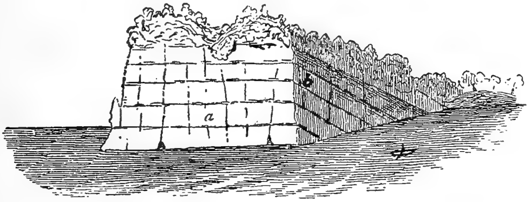


FIG. 11.—APPARENT AND TRUE DIP.

In hilly and mountainous tracts, the exposed ends of strata often present a fallacious appearance of dip, which has occasionally led to mistakes. The appearance referred to is known as "terminal curvature" or "surface creep," and is illustrated in the accompanying figures (Figs. 12*a*, 12*b*). An observer ascending the mountain slopes shown in the diagrams might quite well be deceived by the apparent dip of the beds, if it did not so frequently happen that the true dip of the rocks in such a region is usually exposed in numerous torrent-tracks and gullies. The origin of terminal curvature is obvious enough—being solely the result of weathering. Rain-water insinuates itself between the bedding-planes, and the strata are thus exposed not only to its chemical and mechanical action, but to the more powerful action of frost. The latter tends to force the beds apart—movement taking place chiefly in the line of least resistance, which, of course, is downhill. In this way the edges of the beds are gradually turned over, so as to present an apparent dip which may be exactly opposite to the true inclination of the strata. In high-lying districts this inverting process is often aided by the movement of massive heaps of snow, and by the downward creeping of water-saturated sheets of earthy rock-débris, which tend to drag forward the edges of the beds in the direction of movement.

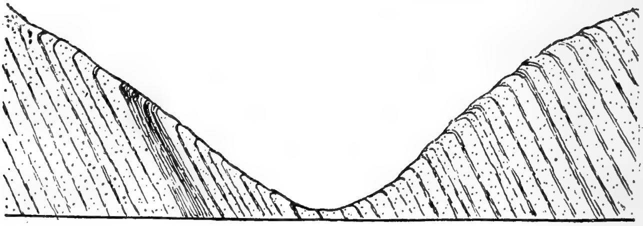


FIG. 12*a*.—TERMINAL CURVATURE IN STEEPLY INCLINED STRATA.

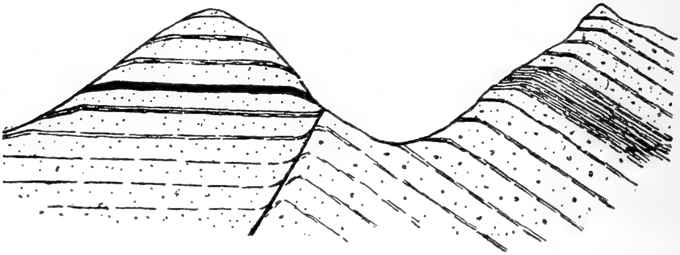


FIG. 12*b*.—TERMINAL CURVATURE IN HORIZONTAL AND INCLINED STRATA.

Outcrop is the term applied to the edges of the strata which appear at the surface. An outcrop may be exposed or visible, or it may be covered and concealed under younger accumulations (see Figs. 13, 14). As a rule, the direction of the outcrop is influenced partly by the inclination of the strata and partly by the form of the ground. When the beds are quite horizontal, every change in the configuration of the surface must affect the direction of the outcrops, which in such a case behave as contour-lines or lines of equal elevation, and follow all the irregularities of the ground. When strata are gently inclined, the outcrops are also strongly affected by the shape of the surface, but this influence gradually lessens as the angle of dip increases, the outcrops, as the beds approach verticality, becoming more and more persistent in direction, and being less and less modified by changes in the form of the ground. When the strata are actually vertical or *standing on end*, the outcrops then run in straight lines across hill and dale, being practically independent of the surface features.

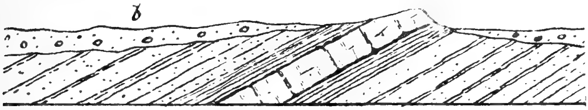


Fig. 13.—Outcrops concealed under Boulder-Clay, *b*.

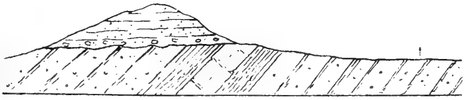


Fig. 14.—Outcrops concealed under Overlying Strata.

A little consideration will show that the *breadth* or *width of an outcrop* must similarly be influenced by the angle of dip and the form of the ground. In the case of horizontal beds, the uppermost stratum, although it may be quite thin, must frequently occupy a relatively wide area and form a broad outcrop. With inclined strata, it is obvious that the outcrops will be broad or narrow according as the dip is low or high—

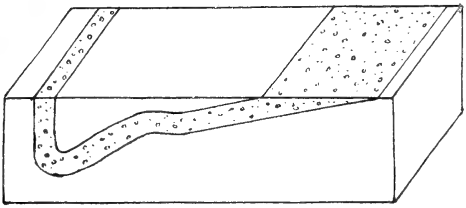


Fig. 15.—Width of an Outcrop affected by Angle of Dip.

the lower the angle of dip, the wider the outcrop (see Fig. 15). As the dip increases, the width of the outcrops gradually diminishes until the strata become vertical, and then the width of outcrop can be no more than the actual thickness of the beds.

The accompanying diagram (see Fig. 16) may suffice to illustrate how the width of an outcrop is affected by surface features. The beds 1, 2, 3, as seen in section, are of equal thickness, but their outcrops, owing to the shape of the ground, vary much in width. Bed 1, appearing upon relatively flat land, yields a broad outcrop; bed 3, forming the surface of a gently inclined plateau, covers a much wider area; while bed 2, coming out on a steep slope, would show upon a map an outcrop somewhat narrower than the true thickness of the stratum.

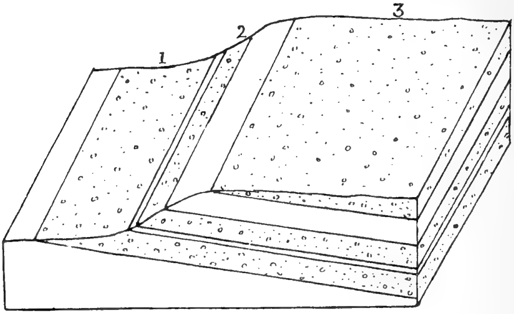


FIG. 16.—WIDTH OF OUTCROP AFFECTED BY FORM OF GROUND.

Strike is a line drawn exactly transverse to the dip. Thus beds with an east dip have a north and south strike. The strike rarely coincides with the outcrop; usually it only does so in the case of vertical strata, the outcrops of which are not affected by the form of the ground. Now and again, however, when the edges of strata inclined at any angle crop out upon a level plain, outcrop and strike may coincide. The term strike is generally used by geologists when they are referring to the average direction of an outcrop. Thus a great succession of strata having a persistent or dominant dip, say towards the north, are said to have an east-and-west strike, no matter how sinuous and irregular the outcrops may be (Fig. 17). Again, when two series of strata with discordant dips occur in juxtaposition, the one set is said to *strike at* or *against* the other. The conditions referred to are shown in the ground-plan (Fig. 18), where the cause of the discordance is the presence of a fault (see Chap. XI.).

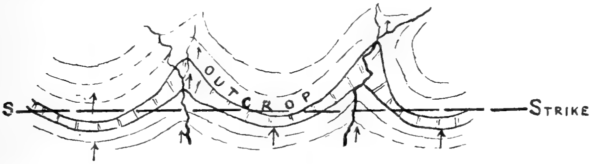


FIG. 17.—OUTCROP AND STRIKE.

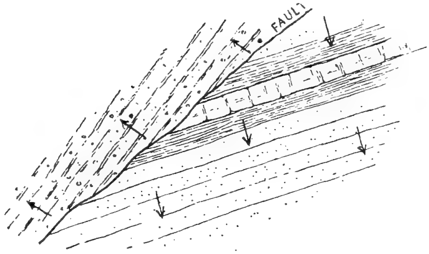


FIG. 18.—STRATA STRIKING AT EACH OTHER.

Curvature of Strata.—Inclined beds are usually, but not always, parts of large curves or undulations. Under certain conditions, as in the case of deltas, we may have a succession of imbricating and interosculating beds, all the members of the series showing a general dip in the direction followed by the sediment-transporting current. Further, it is obvious that the lower beds of a great succession of strata accumulated in a basin-shaped depression, must be more or less inclined, according as the floor of the basin shelves rapidly or gradually. But with continuous sedimentation the inequalities of lake-bottom and sea-floor must eventually be obliterated, and the bulk of the deposits come to occupy an approximately horizontal position. There is little reason to doubt, therefore, that all the great systems of marine sedimentary strata were originally for the most part arranged in successive horizontal layers and sheets. With such exceptions as those referred to above, the inclined position which strata now so frequently occupy must be due to subsequent crustal deformation. Strata originally horizontal have been thrown into gentle undulations and sharper folds, and the tops of such folds and undulations having been gradually denuded away, the truncated ends of the strata now crop out at the surface.

As might have been expected, folds present every degree of complexity. Some are broad and open, others are narrow and compressed; in some the strata are but slightly disturbed—they simply rise and fall in gentle undulations—in others the beds may be twisted, contorted, and confused in the most extraordinary manner.

Monoclinal Flexure.—The simplest kind of flexure is the monocline. This structure is met with chiefly in regions of horizontal or gently inclined strata. It may be shortly defined as a sudden dip or abrupt increase of dip followed by an equally abrupt return to the former horizontal or gently inclined position (see Fig. 19). Frequently the strata in the limb of a monoclinal fold appear attenuated (see Fig. 20), as if they had either been laterally compressed or drawn out. As we shall see later on, this attenuation becomes still more pronounced until the limb of the flexure vanishes and is replaced by a fault or dislocation.

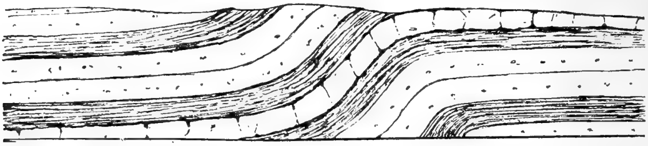


Fig. 19.—Monoclinal Flexure.

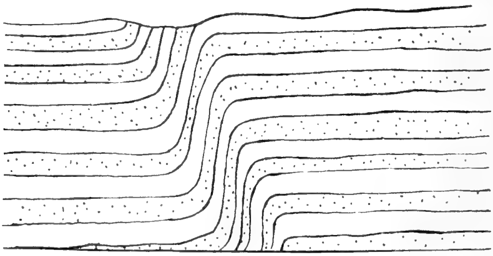


Fig. 20.—Monoclinal Fold showing Thinning of Beds in the Fold.

Quaquaversal and Centroclinal Folds.—Now and again, in regions of gently inclined strata, we encounter dome-shaped and basin-shaped structures. When the strata are dome-shaped they are said to have a quaquaversal dip, *i.e.* they are inclined outwards in all directions from a common point (see Fig. 21). The converse of this structure is seen in a centroclinal fold—the beds dipping inwards from all directions towards a central point (see Fig. 22). But symmetrical or complete quaquaversal and centroclinal folds are of somewhat rare occurrence, and may be looked upon as accidental modifications of normal anticlinal and synclinal folds.

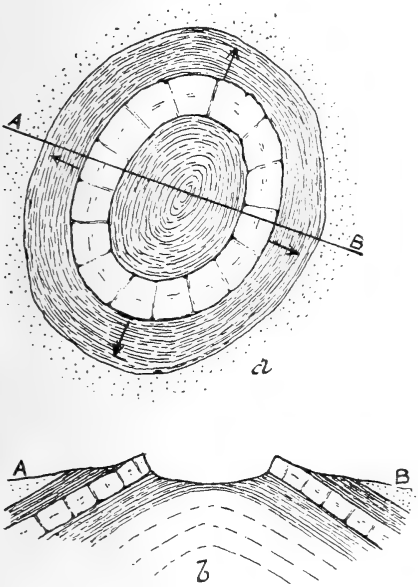


FIG. 21.—QUAQUAVERSAL FOLD.
a, ground-plan; *b*, section along line A—B.

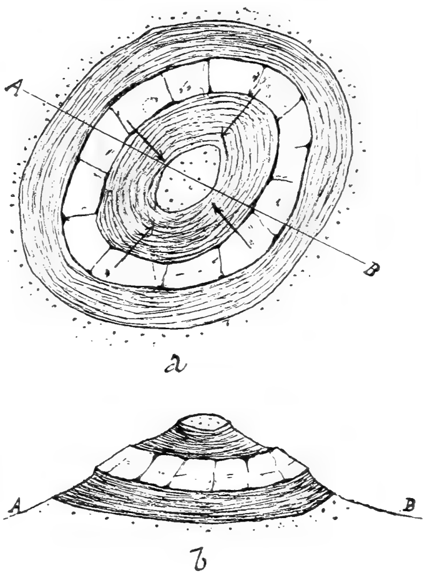


FIG. 22.—CENTROCLINAL FOLD.
a, ground-plan; *b*, section along line A—B.

Normal or Symmetrical Folds.—Strata, as a rule, are folded along axes. This is true of the simplest flexures (monoclines), and of all the more complex folds to be described. The axes or axial planes of normal folds are approximately vertical, and usually extend in straight or gently curving lines. They vary much in length—from a hundred yards or less to many miles. When the strata dip away from such an axis on either side at approximately the same angle, the structure is known as a **Symmetrical Anticline** or *Saddleback* (Plate XXIX.). The converse structure, in which the strata dip in from either side at equal angles to a central axis, is termed a **Symmetrical Syncline** or *Trough* (see Fig. 23). When the inclination of the strata is moderate, individual anticlines and synclines do not usually extend for any distance. A wide region of gently undulating strata often recalls the appearance presented by a slightly rumpled tablecloth—in which the individual wrinkles, sometimes short, sometimes long, succeed each other at inconstant intervals; and while tending, perhaps, to run in a particular direction, are yet frequently straggling and irregular. But when the strata are inclined at higher angles, anticlinal and synclinal folds are apt to extend for longer distances, and to preserve their parallelism more or less persistently. When folding is well developed, it is often possible to follow the axes of individual anticlines and synclines throughout their whole extent. Each fold begins at zero—forming, at first, a quite insignificant "lirk" or crease; little by little, as we follow the axis, the dip of the strata augments until in a longer or shorter distance the maximum inclination is reached, after which the dip usually begins to decrease, and finally the fold dies away. Not infrequently, however, folds increase and diminish in an irregular manner—a great system of parallel anticlines and synclines often consisting of a series of dovetailed and interlocked folds of variable width and extent.

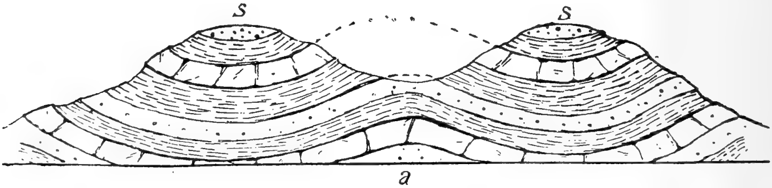


FIG. 23.—NORMAL OR SYMMETRICAL FOLDS.
a, anticline; *s s*, synclines.

When folded strata have been for a long period exposed to denudation, the original crowns or crests of the anticlines have invariably disappeared—the ridges have been gradually

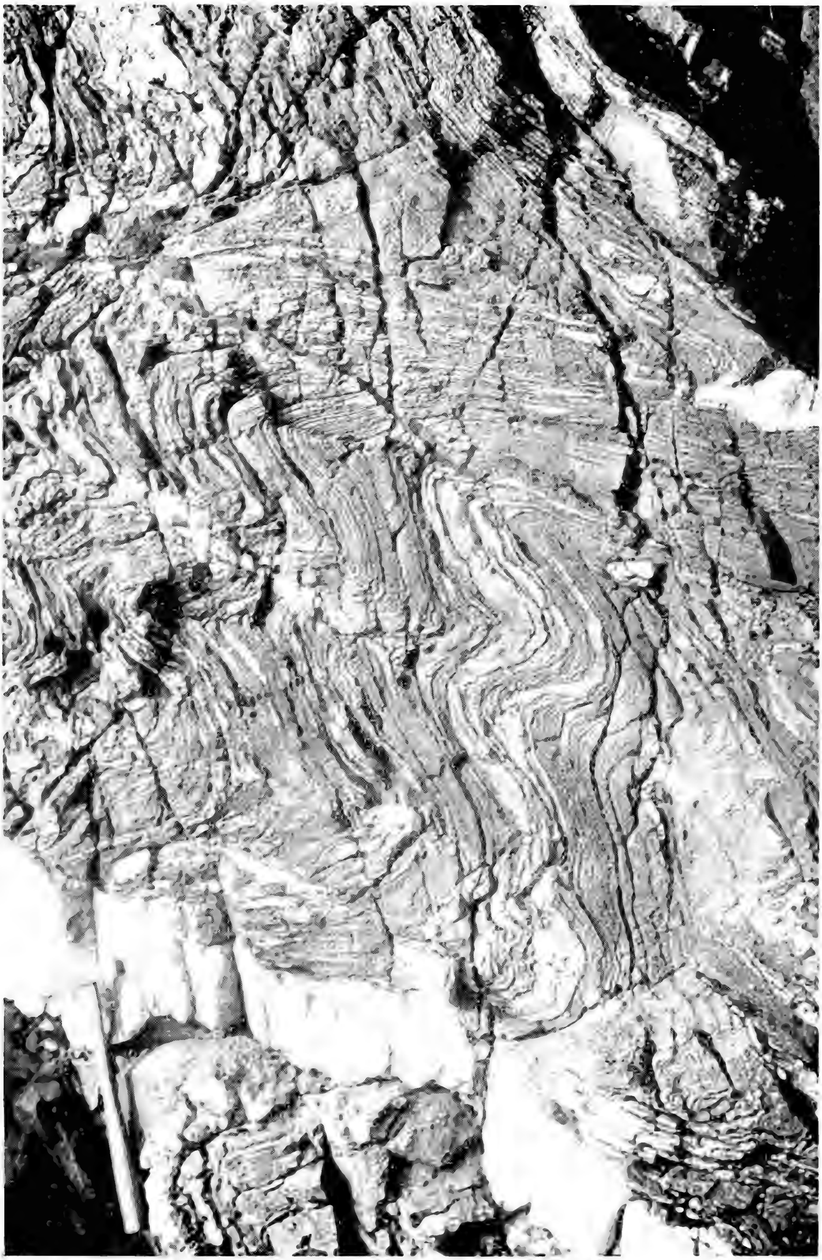
PLATE XXXI.

1. Contorted Alpine Limestone (banded).
Nearly natural size.

2. Contorted Limestone (banded), Glen Mohr, Glen Tilt.

Photo by Dr Flett.

PLATE XXXII.



Contorted Schists, with Quartz Vein, Muchals Caves, Kincardineshire.

Photo by H. M. Geological Survey.

[*Between pages* 136 *and* 137.

lowered by denudation. On the other hand, the synclinal structure has evidently offered greater resistance to the forces of decay, for not infrequently we find that hills are built up of trough-shaped strata. But although the original tops of all anticlinal ridges have, as a rule, disappeared, and synclinal troughs have also been reduced, geologists still speak of these structures as if they were perfect folds. Fig. 24 represents

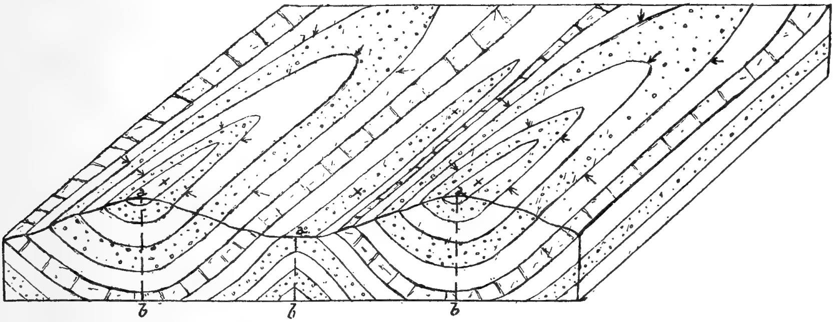


Fig. 24.—Model of Denuded Synclinal and Anticlinal Folds.
a—b, *a—b*, axes of folds.

the model of two synclines with intervening anticline—the arrows indicating the direction of the dip. The dotted lines (*a b*) are the axes of the folds. The section shows the geological structure, and the relation of that structure to the surface features.

Unsymmetrical Folds.—When the axial plane of a fold is inclined at any angle from the vertical, the fold is said to be unsymmetrical. The inclination may be very slight—so slight that the strata on either side of the axis may have much the same angle of dip; or the axial plane may depart so far from the vertical as to be actually horizontal, and the fold then lies on its side. Between these extremes every degree is encountered. As a rule, unsymmetrical folds are closely compressed, the limbs flattened against each other, and the crowns of the arches usually somewhat pointed. Some typical forms are represented in the accompanying illustrations (Figs. 25-30). When the axial plane is so much inclined that one limb of the fold becomes doubled under the other, we have the structure known as an **Overfold** (see Fig.

25). In a fold of this kind the strata which form its lower limb are necessarily turned upside down, and hence the structure

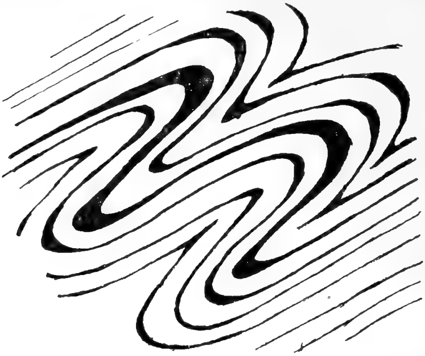


FIG. 25.—UNSYMMETRICAL FLEXURES: OVERFOLDS.

is frequently termed **Inversion.** Unsymmetrical and closely compressed symmetrical folds not infrequently occur together,

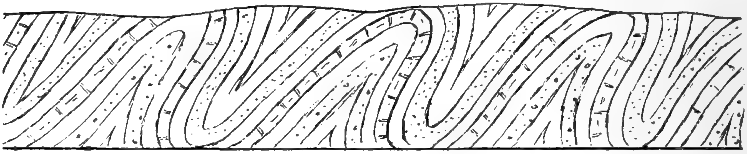


FIG. 26.—ISOCLINAL FOLDS.

but in regions of highly inclined and vertical strata the flexures are usually unsymmetrical, and for the most part

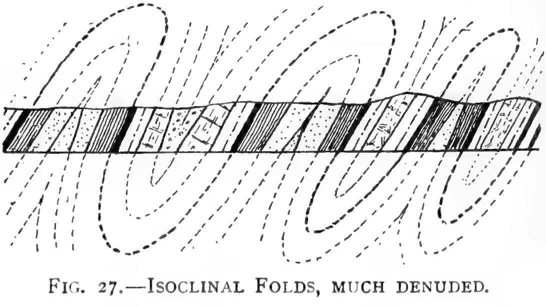


FIG. 27.—ISOCLINAL FOLDS, MUCH DENUDED.

are overfolds. In such cases the successive axial planes very often incline for long distances in the same direction—

the flexures which show this arrangement being termed **Isoclinal folds** (see Figs. 26, 27). As the original crowns of the anticlines have invariably been removed, the truncated beds present the deceptive appearance of a great series of strata, all dipping at high angles in the same direction. In reality, however, as a glance at Fig. 27 will show, the same beds are again and again repeated, so that the series is not by any means so thick as it might at first seem to be. This structure is very well developed in the Southern Uplands of Scotland. **Recumbent fold** (Fig. 28) is the name given to a flexure, the axial plane of which approaches horizontality.

FIG. 28.—RECUMBENT FOLD.

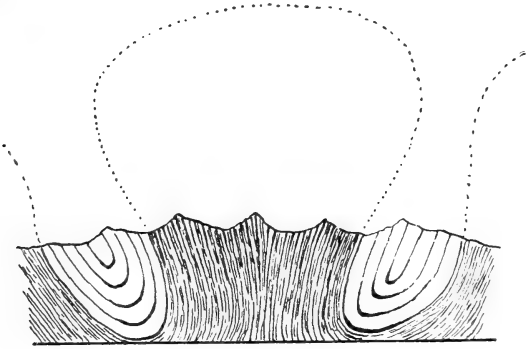


FIG. 29.—ANTICLINAL DOUBLE-FOLD.

It is a structure of frequent occurrence in regions of highly convoluted strata, but is not so common as the ordinary overfold. Another structure, particularly characteristic of the more highly disturbed portions of the earth's crust, is that known as an **Anticlinal Double-fold** (see Fig. 29). In this structure two unsymmetrical synclines approach each other from opposite directions, while in the intervening space the strata are arched into a great anticline. The crown of the anticline has invariably disappeared, so that the truncated strata are seen to dip in from both sides towards the axial plane. Since the beds within the anticline are much compressed below while they open out above, they present the appearance known as **fan-shaped structure** (see Fig. 30).

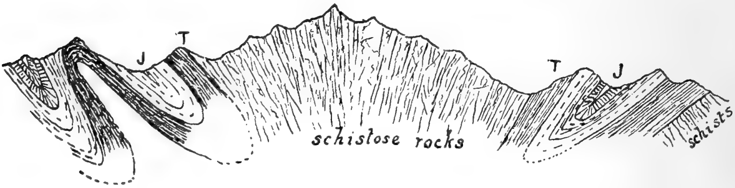


FIG. 30.—SECTION ACROSS MOUNT BLANC, SHOWING FAN-SHAPED STRUCTURE.

All the several kinds of unsymmetrical folds described in the preceding paragraph occur in regions which have been subjected to some dominant movement of the crust—either of elevation or depression. When a broad zone has bulged up under lateral pressure to form a mountain chain, we have, as in the Alps, one great arch composed of numerous subordinate wrinkles or minor folds and flexures. A complex arch of this kind is termed an **Anticlinorium** (see Fig. 31).

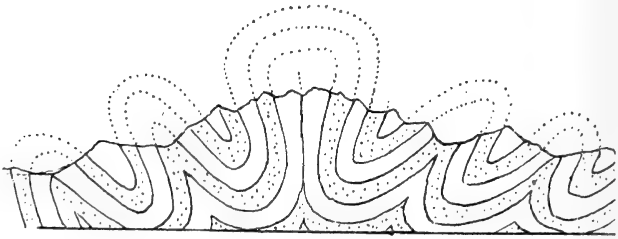


FIG. 31.—DIAGRAM OF AN ANTICLINORIUM.

If the arch be simple—a broad anticlinal fold with no conspicuous wrinklings or flexures—it is known as a **Geanticline.** The converse structure, resulting from the depression of a broad zone, is termed a **Synclinorium,** when the great trough is complicated by many subordinate foldings, and a **Geosyncline** when the trough is simple.

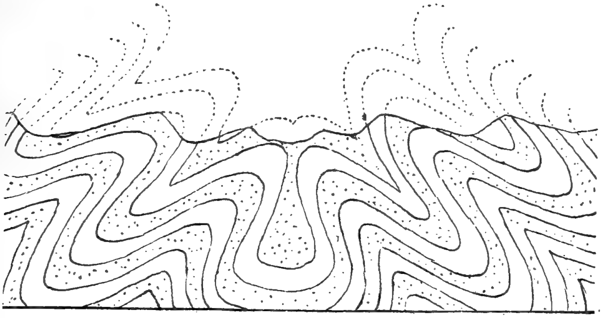


FIG. 32.—DIAGRAM OF A SYNCLINORIUM.

Contorted Strata.—When strata are so unsymmetrically and abundantly folded that it becomes difficult or impossible to trace out the individual flexures and crumplings—the whole forming an irregular complex of folds—they are said to be contorted (see Plates XXX.-XXXII.). Such contorted rocks are frequently associated with the several kinds of unsymmetrical folds described in the preceding section. In all highly folded and corrugated strata, the rocks have obviously been subjected to great compression. This is seen in the peculiar thinning and thickening undergone by the strata—the beds becoming attenuated in the limbs of the folds, and swelling out again in the cores of the arches and troughs (see Plates XXXI., XXXII). It would seem, in fact, as if, under compression, the solid rocks had been compelled to yield and to behave like plastic bodies. The evidence of such shearing and flowing is conspicuous not only in the larger folds, but in the smallest crumplings visible to the naked eye. Indeed, when the rocks are sliced and examined under the microscope, they continue to show precisely the same structures. It is thus no exaggeration to say that folds vary in dimensions from great flexures measuring hundreds of yards across, down to puckerings and crumplings so minute that they only become visible under the microscope (see Plate V. 4).

If in the case of contorted strata the individual beds and their subordinate laminæ have become distorted, it is not surprising that their individual constituents should similarly yield evidence of compression. Thus the rounded stones of a conglomerate (Plate XXI. 3) are often flattened against each other and drawn out into elliptical or lenticular forms, while fossils are frequently distorted in like manner. This process of deformation has often proceeded so far as to result in the more or less complete alteration of the rocks, the original characters being either much obscured or even entirely obliterated. But the further consideration of such changes must be deferred until we come to discuss the phenomena of slaty cleavage and metamorphism.

Origin of Folds.—The various folds described above are obviously the result of lateral compression brought about by the sinking of the superficial crust of the globe upon the cooling and contracting interior. If we think of it, there must be a gradual passage downwards from the cooled crust into the still uncooled nucleus. At some depth from the surface, therefore, a level will be reached at which the interior has not yet begun to cool and contract. Theoretically, we may consider all the matter above that level as constituting the crust. The lower section of the crust, reposing immediately upon the uncooled nucleus, is cooling and therefore contracting, and must obviously be in a state of tension to which it will seek to yield by rupturing. Not that fissures or rents will actually be formed, for the enormous compression exerted by the upper crustal layers will necessarily prevent anything of the kind taking place. The stretching of the crust by lateral tension must diminish upwards, until a level is attained where it will cease altogether. Above that level the crust is no longer in a state of lateral tension, but in one of lateral compression—it is not stretching but shrivelling. And the lateral compression which causes the superficial crustal shell to shrivel increases upwards, and is therefore greatest at the surface. There are thus two kinds of contraction to which the crust is subjected, namely, circumferential below and radial above. When the former is in excess, stretching with tendency to rupture is most marked; where the latter prevails, compression is dominant; where the one equals the other there is no strain. It is therefore only the crustal shell above this neutral zone or "level-of-no-strain" which is liable to become folded. How thick that shell may be we do not know, but as the folded rocks in some mountain chains reach a thickness of ten miles or more, the upper crustal shell must be of that thickness at least. Although folded strata are met with very generally, in Old and New Worlds alike, nevertheless we now and again enter regions of great extent, over which the strata have retained their original horizontal arrangement. It is notable, further, that while gently undulating strata often extend throughout vast areas, highly folded and contorted rocks tend to occur in zones or belts. It would thus seem that the earth's crust yields unequally to the lateral compression induced by its subsidence on the cooling and contracting interior. The younger mountain ranges of the globe—the Alps, the Himalayas, the Andes, the Rockies, etc.—are composed essentially of highly disturbed and complexly folded and contorted rocks, and are believed, therefore, to indicate zones of weakness, along which relief from pressure has been readily obtained. Similarly, much more ancient zones of steeply flexed and folded rocks, occurring, it may be, in low-lying regions, show geologists where gigantic mountains formerly existed, and assure them that from the earliest times the crust has found relief from lateral pressure by buckling up along lines of weakness.

Some further remarks on folding and its results will be found in the following chapter.

CHAPTER X

JOINTS

Joints, Close and Gaping. Joints in Bedded Rocks—Master-joints, Dip- and Strike-joints. Joints in Igneous Rocks—in Granitoid Rocks, Prismatic Joints. Joints in Schistose Rocks. Slickensides. Origin of Joints—Contraction, Expansion, Crustal Movements.

JOINTS are superinduced divisional planes which traverse rocks in different directions and at various angles, so as to allow of their ready separation into larger and smaller blocks and fragments of regular or irregular shape. The faces of a joint are generally smooth and flat, but in certain cases (as in many crystalline igneous rocks), they are often somewhat curved. In fresh, unweathered rocks, joints are usually inconspicuous, the faces being sometimes in such close apposition that the fissure can hardly be detected. The presence of even the closest joints, however, is often betrayed by the alteration of the rock induced by percolating water—the degree of alteration naturally depending to a large extent upon the character of the rock. In the case of red sandstone, for example, the position of the joints is frequently indicated by more or less vertical lines and bands of bleached rock. In limestone, again, the joints tend to gape, as might have been expected from the ease with which that rock is dissolved by acidulated water. The faces of joints are frequently coated with a pellicle of brown or yellow iron-oxide; or with other depositions from aqueous solution, such as calcite, barytes, quartz, chalcedony, etc. Gaping joints are in like manner often filled with similar products—and are then described as veins, which may vary in width from less than an inch up to many feet. The phenomena of mineral veins,

Ripple-marked Sandstone traversed by Joints, near Kinghorn, Fife.

Photo by H.M. Geological Survey.

PLATE XXXIV.

Joints in Greywacké, Currarie Port, South Ayrshire.

Photo by H.M. Geological Survey.

[*To face page* 145.

however, will be considered in a later chapter, under the general head of Lodes.

As a rule, the more important joints in solidified rocks of all kinds tend to be somewhat open, or, at all events, are most readily recognised at and for some distance down from the surface, becoming less and less conspicuous as they are followed to greater depths. It is impossible to doubt that these appearances are due to epigene action, the influence of which must gradually die out downwards. The opening of the joints in readily soluble rocks like limestone, may be safely attributed to percolating water; but, in the case of relatively insoluble rocks the fissures can hardly have been opened by the same means, and are more likely to have been widened by changes of temperature. In temperate latitudes, however, diurnal and seasonal changes of temperature do not affect rocks beyond a few feet from the surface, and can scarcely account, therefore, for the phenomena referred to. We must remember, however, that during relatively recent geological times the present temperate latitudes of Europe and North America experienced certain remarkable climatic vicissitudes—having sometimes been subjected for lengthy periods to the rigours of an arctic climate, while at other times the conditions would seem to have been more genial than they are now. Under such alternations of cold and heat the rocks could hardly fail to have been affected to a much greater depth than is possible at present. We know that in high latitudes the ground is permanently frozen to a depth of over a hundred feet, and that the heat of summer suffices to thaw only a thin superficial stratum. Were glacial conditions, therefore, again to supervene in temperate latitudes, we cannot doubt that with increasing cold frost would penetrate ever deeper and deeper—the rocks contracting and all moisture becoming frozen to depths approximating those reached by frost in sub-arctic regions. With the gradual return of genial conditions thawing would ensue until no part of the ground remained permanently frozen. To this process of alternate freezing and thawing, repeated again and again throughout the long glacial cycle, we ought perhaps to assign the opening up of joints at considerable depths from the earth's surface.

Joints in Bedded Rocks.—Sedimentary rocks are usually traversed by two sets of joints, perpendicular to the planes of bedding, and intersecting each other at approximately right angles. Not infrequently these joints run roughly parallel for long distances, and when they do so they are known as *Master-joints*. Usually, however, it is impossible to follow individual joints very far, and the parallelism of a series is only approximate, for often enough one joint runs into another. In most cases, indeed, individual joints seem to die out in a few yards, and to be succeeded after a longer or shorter interval by one or more following the same general direction. The width of rock between adjacent joints, belonging to the same parallel series, is very variable. In some cases it may be many feet or even yards; in other cases it may be considerably less than a foot. In certain thin-bedded strata, for example, so closely set are the joints that the rock breaks up readily into small cubes and parallelopipeds. In addition to the more or less regularly intersecting main joints, numerous subordinate joints may traverse a rock in many different directions; and when such is the case, the system of main joints becomes obscured or unrecognisable—the irregularly fissured rock breaking up into a rubble of larger and smaller angular fragments (see Plates XXXIII., XXXIV.).

When bedded rocks are inclined, the intersecting main joints are known as *dip-joints* and *strike-joints* respectively—the former running in the direction of the dip or inclination of the beds, while the latter cross these at approximately right angles. Strike-joints are usually more pronounced than dip-joints. To this rule, however, there are many exceptions—sometimes the latter being more conspicuous than the former, while not infrequently the one set is hardly better developed than the other.

The joints that traverse a succession of alternating strata of limestone, shale, sandstone, etc., are often interrupted and sharply shifted to the side as they pass from one bed to another. Often, indeed, certain beds in a series are more regularly divided than the immediately overlying and underlying strata the jointing of which may be very irregular, and more abundant or less so than that of the intermediate strata. In such cases the divisional planes of the several beds appear to be more or less independent.

While regular jointing may be met with in all kinds of derivative rocks, it is best displayed, as a rule, in fine-grained deposits of homogeneous composition, as in limestones, freestones, flagstones, coal, etc. Common household coal, for example, is divided by three sets of planes disposed at right angles to each other: namely (*a*) planes of bedding, with a dull sooty surface, and (*b*) and (*c*) joint-planes with bright surfaces. One set of joints (*b*) runs in the direction of the inclination or dip of the bed, and is termed by miners the "end of the coal," the other set (*c*) traverses the bed at right angles to the "end," and is known as the "face or cleat of the coal." The "face," therefore, coincides with the *strike* of the strata. In a coal-mine cross-galleries are driven in the direction of

PLATE XXXV.

TABULAR JOINTS IN GRANITE, SUMMIT OF GOATFELL, ARRAN

Photo by H.M. Geological Survey.

[*To face page* 146.

the "end" (*i.e.* with the dip or inclination of the strata), while the working-galleries are driven along the "face" (*i.e.* the strike), and they necessarily follow, therefore, a level-course. So long as the inclination of the strata remains constant in direction, the working-galleries must follow a straight line at right angles to the dip, but with any change in the direction of the latter there will necessarily be a corresponding change in the direction of the "level-course."

Excellent examples of regular jointing are exhibited by the thick Carboniferous Limestones of Ireland and England—the main or master-joints crossing each other nearly at right angles, and preserving their direction for long distances. The Old Red Sandstone strata of N.E. Scotland, which are so finely displayed in numerous coast-sections, afford equally good illustrations of the same structure.

Joints in Igneous Rocks are seldom as regularly arranged as those of sedimentary strata; indeed, they are frequently so very irregular that no system or arrangement can be recognised. In other cases, however, the division-planes show a modified regularity, following determinate directions like the master-joints described above; while in yet other cases they are so symmetrically disposed as to confer a prismatic columnar structure on the rock they divide.

The joints in granite are often wonderfully regular—two sets of vertical or steeply inclined division-planes intersecting at various angles, which often do not depart widely from right angles. The rock thus tends to be divided into columnar masses that vary in shape according to the character of the joints (which may be straight or curved), and the angle at which they intersect. Sometimes the joints are widely separated, so that large monoliths can be obtained; at other times they are so closely set that the rock breaks up into a rubble of small fragments. The main vertical joints are often accompanied by minor irregular joints the presence of which necessarily prevents the extraction of large blocks. In addition to its vertical division-planes granite often exhibits a set of cross-joints, arranged at approximately right angles to the others. These cross-joints may be horizontal or inclined, and often give the rock a kind of bedded appearance, at least towards the surface (Plate XXXV.). They are seldom, however, so even as planes of bedding. Usually they are somewhat undulating, and run into each other so as to divide the rock between the vertical joints into a series of lenticular and interosculating layers or sheets. This structure when viewed from a little distance sometimes simulates the appearance of false-bedding. These curious joints are most conspicuous towards the surface, where they are often only a few inches apart. The width between them, however, increases with the depth, while at the same time the joints become closer and more discontinuous, until at last they disappear. The joints in question are thus obviously related to the surface, and this relation is rendered still more evident by the fact that they are always approximately parallel to the surface. Thus, when the ground is level the cross-joints are horizontal; but when it is inclined, the joints have a similar dip. In a broad, dome-shaped mountain of granite, for example, the rock often appears to consist of a series of rudely concentric shells, which at the summit are horizontal, but from thence dip outwards in all directions, coinciding roughly with the average fall of the ground.

Cross-joints of the kind described above are not confined to granite, but occur in other massive eruptive rocks. They have been observed, for example, in some syenites and quartz-porphyries, but are seldom so well developed (see Plate XXXVIII.). [Even homogeneous sedimentary rocks, such as limestone and freestone, now and again exhibit a similar structure, which cannot be mistaken for true bedding.]

The columnar structure of granitoid rocks due to jointing, is by no means so well developed as that of certain other igneous rocks. Many basalts, for example, are jointed so symmetrically that the rock looks like an organised aggregate of prismatic columns (see Plate XXXVII.). When this structure is fully developed, as in the well-known rocks of Fingal's Cave and the Giant's Causeway, the columns tend to assume hexagonal forms. But although six-sided columns are common enough, yet the faces of the prisms are seldom equally developed, while many columns may show fewer or more faces than six, so that trigonal, tetragonal, pentagonal, and polygonal forms are often associated. This prismatic structure is always developed at right angles to the planes of cooling. Hence, when the rock is in a horizontal position—the upper and under surfaces being planes of cooling—the columns are vertical. When, on the other hand, the molten rock has cooled and solidified in a vertical fissure, the walls of this fissure form the cooling-planes, and the columns are therefore horizontal. In the case of *intrusive* sills or sheets of basalt, the columns sometimes extend continuously from one cooling-plane to another; in dyke-like intrusions, however, they are usually not continuous, but separated half-way by an irregular line. Now and again, indeed, small dykes and veins of basalt are wholly composed of successive thin belts or layers of prisms—the prismatic layers being separated by a series of roughly parallel fissures (see Figs. 73, 74, p. 204). In lavaform rocks the columnar structure seems likewise to be related to planes of cooling—the columns being vertical or inclined according as the rock has cooled upon a horizontal or an inclined surface. Not infrequently, both in lavaform and intrusive rocks, the columns are curved; and in most cases, whether curved or straight, they are usually intersected at more or less regular intervals by transverse or cross-joints, which in some few cases show a ball-and-socket arrangement—the convex surface of one segment fitting into the concave surface of the next overlying or underlying block. For it is to be noted that the convex surfaces of the segments in adjacent columns, or even in one and the same column, do not always point in the same direction.

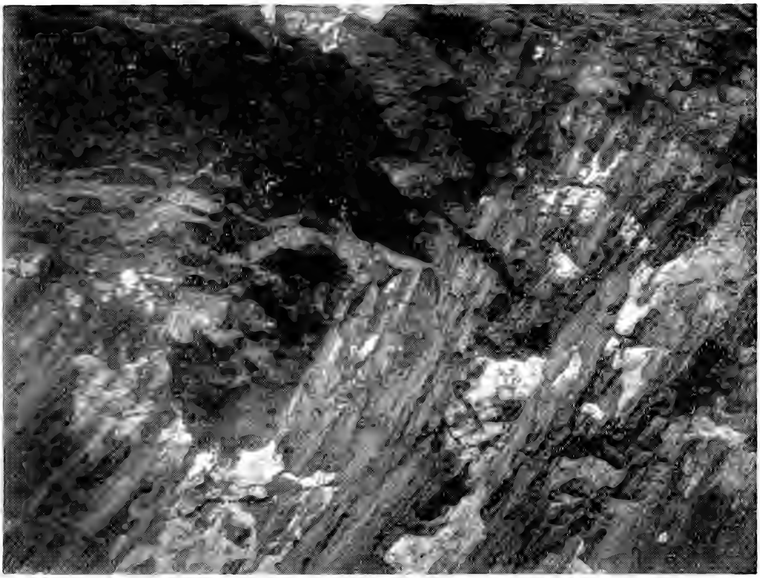
The columns or pillars vary much in size. In some thin dykes of basalt they may be less than an inch in diameter and only a few inches in length, while in thick sheets and lava-flows they may attain a thickness of 1 or 2 feet, and a length of 200 feet or more. Prismatic jointing, although as a rule best developed in fine-grained basic igneous rocks, is by no means confined to these, for it is often well developed in andesites, quartz-porphyries, and now and again in obsidian. [Neither is the structure in question confined to igneous rocks. Even sandstone and coal occasionally exhibit a superinduced prismatic structure. In such cases the rocks have been influenced by the presence of intrusive igneous masses. Excellent examples occur in the Scottish coalfields, where whole beds of coal have been converted into a kind of prismatic coke; while at and near their contact with eruptive rock the sandstones often acquire a kind of rude columnar structure.]

Joints in Schistose Rocks.—As schistose or foliated rocks differ much in composition and structure, they might have been expected to show considerable variety in the character of their jointing. Those of them in which the foliated structure is well developed are occasionally divided by vertical or steeply inclined joints, but these are very rarely arranged symmetrically, and no system of intersecting joints like those of sedimentary strata can be detected. Now and again, however, granitoid gneiss is crossed by division-planes which have a general resemblance to the joints of granite. But, as a rule, the jointing of schistose rocks is irregular and capricious.

Slickensides (Plate XXXVI.).—The surfaces of joints in all kinds of rock are often smoothed and marked by parallel ruts and striæ, as if the opposite rock faces had been ground and rubbed against each other. These *slickensides*, as they are termed, are frequently coated with a skin of mineral matter, which naturally shows a cast of the opposite joint face, and thus has the appearance of having itself been smoothed and striated. In opening up a joint occupied by a thin vein of mineral matter, it is often possible to detach complete segments of the vein, which yield a cast of both joint faces. While slickensides are not confined to any particular areas, they yet tend to be most abundantly developed in regions where considerable crustal movement or rock-displacement has taken place. They often occur, for example, in the joints of rocks near lines of fracture and dislocation of the crust, and, as we shall learn presently, the walls or faces of such dislocations themselves frequently exhibit the same smoothed and striated appearance.

Origin of Joints.—No one cause suffices to explain all the phenomena of joints. In many cases we can hardly doubt that these superinduced division-planes are simply fissures of retreat, formed during the consolidation and solidification of the rocks in which they occur. Some joints, again, are of such a character as to show that considerable force was required for their production, and these are suggestive, therefore, of crustal movements of some kind. The precise origin of others, however, is still obscure. The more obvious causes which have led to the jointed structure of rocks may be considered under the headings of *Contraction*, *Expansion*, and *Crustal Movements.*

CONTRACTION.—Any moist and plastic rock, such as clay, necessarily



1. Slickensides, partly coated with Mineral Matter (White).

2. Slickensides, not coated.

[*To face page* 150.

contracts while drying, and in this way becomes more or less abundantly cracked or fissured. Possibly this may be the origin of many of the minor or subordinate irregular joints of sedimentary strata, but it does not account for the vertical intersecting joints which are so characteristic of these rocks. The passage from the non-crystalline to the crystalline condition also involves contraction, and thus we may believe that the crystallisation of certain chemically formed deposits may have been the cause of their jointed structure. To the same cause must undoubtedly be attributed most of the division-planes occurring in crystalline igneous rocks, such as the vertical joints in granite, and the prismatic jointing of basalt and other eruptive rocks. The cross-joints of granite, however, cannot be accounted for in this way. The simple fact that they are present only in the upper part of a rock-mass and disappear entirely at lower levels suffices to show that they have not the same origin as the vertical joints between which they have been developed. It is otherwise with the cross-joints of basalt, etc., which appear to be of the same nature as the prismatic joints with which they are associated—fissures of retreat, due to the contraction of the rock in cooling. The peculiar manner in which basalt and many other igneous rocks weather is somewhat suggestive. Prismatic columns which have been long exposed often lose their angular form, the individual segments or blocks assuming a spheroidal shape, so that the rock appears as if built up of vertical rows of globular ball-like or cheese-like bodies. Each of these spheroids exfoliates in successive concentric shells—a fraction of an inch in thickness—and the external ones may be readily detached by the hammer. The shells, however, become more adherent and less conspicuous as we penetrate the rock until they cease to appear. This peculiar kind of weathering is not confined to rocks which show a prismatic structure, being met with not only in non-columnar basalt but in many other igneous rocks, as in some pitchstones, granites, diorites, porphyries, etc. The weathering often proceeds so far that the exfoliating crusts break down into a kind of earthy or sandy grit, till nothing of the original rock may be left save a few scattered balls or cores. It is supposed that the shell-like structure betrayed by weathering is really original, the centre of each spheroid having been a centre of contraction. So long as the rock is fresh the structure remains invisible, and only becomes apparent when weathering supervenes. This is a plausible or even probable explanation of the phenomena, but it does not quite carry conviction. The perlitic structure of glassy rocks (which is due to the presence of numerous minute and roughly concentric cracks produced during cooling and contraction) has been cited as an example on a small scale of that spheroidal structure of basalt, etc., which is only revealed by weathering. All one can say is, that nothing comparable to perlitic structure has ever been detected by the microscope in those crystalline rocks which weather spheroidally—there is nothing in the microscopic appearance of basalt, diorite, etc., that would lead one to expect that such rocks should exfoliate in successive concentric shells. While, therefore, we need have no doubt as to the vertical- and cross-jointing of basalt, etc., being due to contraction, the origin of the shell-like structure exhibited by weathering and decomposing rocks is still an open question.

EXPANSION.—Rocks of all kinds when subjected to heat will necessarily expand, and when cooling will contract. As a result, they become rent and fissured. Excellent examples are seen in the Scottish coal-fields. Thus beds of common coal, subjected to the heat of molten rock erupted in their immediate neighbourhood, have been converted into prismatic coke. In such cases the coal having been subjected to destructive distillation has, of course, lost some of its constituents. Even siliceous sandstones and argillaceous shales invaded by eruptive rock-masses often acquire a rudely columnar structure. But sun-heat is a much more general cause of expansion. This is probably effective in all latitudes, but naturally enough its results are best studied in dry tropical and subtropical regions. In temperate and higher latitudes, the effect of insolation is obscured or entirely concealed by the much more energetic action of frost and other epigene agents. In warm and relatively rainless regions the rocks are heated up during the day to a high temperature—consequently their superficial portions expand to such an extent that they often become detached, and bulge up from the underlying rock of which they form a part. In this way igneous rocks sometimes acquire a superficial flaggy structure. When night falls rapid radiation ensues, and the rocks quickly contract, so that the superficial portions tend to break up more or less rapidly. In the case of fine-grained homogeneous rocks, the highly heated surface often peals away in thin sheets which curl up, and are readily removed by the wind. The flags produced by desquamation naturally coincide with the surface, so that they may be curved, inclined, or horizontal according as the rock-surface is rounded, sloping, or level. Their direction is, therefore, independent of any internal rock-structure.

The cross-joints of granite may, in like manner, owe their origin to epigene action. All the phenomena connected with them seem to point to that conclusion. They are always approximately parallel with the surface, are most numerous and strongly marked in the superficial part of the rock, and as they are followed downwards, appear at longer and longer intervals, becoming, at the same time, more interrupted in their course and less conspicuous, until finally they disappear. Further, it may be noted that the "grain" or "rift" of the granite—*i.e.* the direction in which the rock splits or breaks most readily, is parallel with the cross-joints. Not only so, but, like the latter, it is most marked near the surface, and gradually dies out downwards as they disappear. Now there is no apparent petrographical structure to account for this "grain," and its coincidence with the cross-jointing. The rock consists throughout of a heterogeneous pell-mell aggregate of minerals. It is otherwise with sedimentary rocks, the "grain" or "rift" of which naturally coincides with planes of deposition, just as the "grain" of a schistose rock coincides usually with planes of foliation. The grain of some crystalline igneous rocks is due, likewise, to a roughly parallel arrangement of their constituent

PLATE XXXVII.

Columnar Basalt, Pettycur, Kinghorn, Fife.

Photo by H.M. Geological Survey.

PLATE XXXVIII.

CURVED JOINTS IN FELSITE, BLACKWATER FOOT, ARRAN.

Photo by H.M. Geological Survey.

[*Between pages* 152 *and* 153.

minerals, as in the case of phonolite, which, owing to the orientation of its dominant minerals, often cleaves more or less readily into parallel slabs and flags. So again, many lavaform rocks, and even occasionally intrusive sheets or sills and dykes, have a tendency to split most readily in the direction of flow. In most cases the "grain" is determined by the more or less obvious parallel arrangement of the rock-ingredients—a rock dividing most readily when the orientation is best developed. When such arrangement is very obscure or not at all visible, as in heavy lavas and sills, the coincidence of the "grain" with the direction of flow seems, nevertheless, to show that the "grain" is an original structure. No such structures, however, occur in normal granite—the grain of which certainly does not depend on the alignment of its constituents. Neither does it bear any relation to possible movements of the original molten mass, nor to the vertical joints or fissures of retreat produced by contraction. It has apparently been superinduced in granite by epigene action—and is not improbably due to the expansion and contraction induced by seasonal and secular changes of temperature. This conclusion gains support from the fact that cross-jointing and coincident "grain," similar to those of granite, have been observed in other kinds of eruptive rock. Cross-jointing has even been superinduced in the upper parts of fine-grained homogeneous aqueous rocks, where consolidation from a state of igneous fusion is, of course, excluded. But if such structures can be superinduced by epigene action, we may be led to suspect that the exfoliating spheroids of weathered basalt, etc., are likewise independent of any original structure due to contraction while the rock was cooling—that, in short, the concentric shells are solely the result of changes of temperature and of weathering generally.

CRUSTAL MOVEMENTS.—While it may be admitted that the tension brought about by the causes already considered must have induced the formation of fissures in many kinds of rock, there is yet a large class of joints which cannot be thus explained. The regular intersecting systems of master-joints in sedimentary strata are suggestive rather of powerful mechanical stress and strain. The strata have been cut through as smoothly as if they had been severed by a knife ; and this is true not only of homogeneous rocks, such as limestone, but of heterogeneous aggregates like conglomerate. In the latter rock the superinduced division-planes pass without interruption through stones and matrix alike, even although the stones may consist of much harder and tougher material than the matrix in which they are embedded. Had such joints been the result of contraction only, the stones would simply have been pulled out of the matrix on one side of a fissure and left projecting from the surface of the other. The general opinion is that joints of this kind are the result of crustal movements. It is not difficult to conceive how strata, subject to compression and tension during such movements, should have cracked and become fissured. We seem thus to get a ready explanation of the strike-joints, for it is along the axes of folds that strata would be subject to the greatest compression and tension. It seems also reasonable to infer that dip-joints might have originated at the same time. Various interesting experiments by the famous French geologist, A. Daubrée, tend to show that two series of intersecting joints might be expected to result from powerful crustal movements. Daubrée experimented upon long rectangular plates composed of various substances, and demonstrated that these, when subjected to the strain of torsion, were traversed by two sets of approximately parallel cracks, one system crossing the other at angles of 70° to 90°, and thus closely simulating the intersecting master-joints of stratified rocks.

Mr W. O. Crosby has suggested another explanation of the normal intersecting joints so characteristic of bedded rocks. He thinks that these are probably due to earthquake action. The fractures produced by vibratory movements of the earth's crust he shows must be plane, parallel, intersecting, and normally vertical, thus possessing all the characteristics of master-joints. Mr Crosby thus appeals to a *vera causa*, but his theory does not exclude that which would attribute dip- and strike-joints to folding. It affords a better explanation, however, of the vertical intersecting joints of horizontal strata, which can hardly be accounted for by torsion. Undisturbed horizontal strata, covering wide regions, are often as regularly jointed as strata which have been folded. In such cases, therefore, we may suppose the jointing has most probably resulted from the passage of earthwaves through the rocks, the alternate compression and tension having been sufficient to produce fissuring. As there is possibly no part of the earth's crust which has not experienced earthquake shocks and vibrations, such crustal movements may have played a more important rôle in the formation of joints than might be suspected. The great crustal movements which resulted in the buckling up and folding of strata in gigantic mountain chains, must often have induced severe earthquakes, caused by the sudden yielding of rock-masses to tension; but the fissuring and shattering due to the passage of such vibrations or waves of elastic compression could not now be distinguished from the ordinary effects of folding and torsion.

CHAPTER XI

FAULTS OR DISLOCATIONS

Normal Faults. Dip-faults and Strike-faults—their effect upon Outcrops. Oblique Faults. Systems of Faults. Step-faults. Trough- and Ridge-faults. Shifting of Faults. Reversed Faults. Transcurrent Faults. Origin of Faults.

HAVING now learned that rocks of all kinds are more or less fissured, and that no small proportion of the joints by which they are thus traversed appear to owe their origin to crustal movements, we must next make the acquaintance of fissures of another kind, known as Faults or Dislocations. These are doubtless due likewise to crustal movements, but they differ from joints in being not mere cracks or rents, but fissures of displacement. The rocks on one side of a fault are thus abruptly truncated and brought against younger or older rocks on the other side. Three types of faults are recognised, namely, *Normal Faults* (or *Downthrows*), *Reversed Faults* (or *Overthrusts*), and *Transcurrent Faults* (or *Transverse Thrusts*).

NORMAL FAULTS.—These dislocations are rarely, if ever, quite vertical, although in natural exposures they sometimes appear to be so. But when they are followed downwards, as in mining operations, they are invariably found to be inclined, the degree of inclination varying, it may be, from point to point, so that in places they occasionally show verticality. The general inclination of a fault from the vertical is termed the **hade**, and this, in the case of normal faults, is always in the direction of the downthrow. The degree of deviation from the vertical is quite indeterminate; but, as a general rule, the larger are more steeply inclined than the smaller faults. But to this rule many exceptions occur. The amount of vertical displacement is known as the **throw** * of a fault, and is measured by protracting a line in a horizontal direction (as in Fig. 33), across the fault from the truncated end of some particular bed (*a*) until a perpendicular (x—a^2) dropped from the protracted line can reach the other end of the selected stratum on the opposite side of the fault. Miners seldom use the term *fault*, but speak of *downthrows* or *downcasts*, and *upthrows* or *upcasts*, according to the direction in which they are working. Thus the faults (F^1, F^2) shown in Fig. 33 would be described as downcasts or downthrows if they were encountered by a miner working in the direction from A to *a*, or from *a* to A, but he would speak of them as upcasts or upthrows, if he approached them from the direction of C to a^2, or from B to a^2.

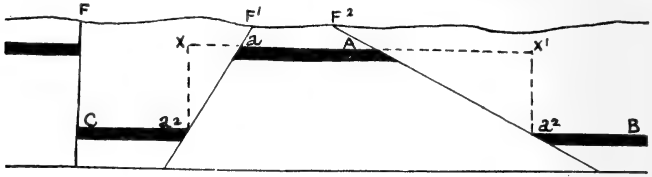


Fig. 33.—Normal Faults in Horizontal Strata.

It is obvious that in Fig. 33, representing faulted horizontal strata, the amount of throw is equal to the thickness of the beds lying between x—a^2 and x^1—a^2; but this is not so in the case of inclined strata. In Fig. 34, for example, the amount of vertical displacement (a—x) is in excess of the thickness of the strata measured as in the preceding illustration (Fig. 33) at right angles to the planes of bedding (a^1—a^2).

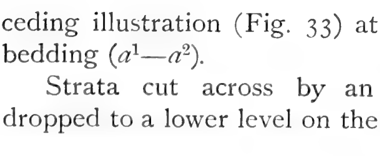


Fig. 34.

Strata cut across by an inclined fault are not only dropped to a lower level on the downthrow side, but the fault

---

* The amount of displacement varies indefinitely. Some faults are mere slips of a few feet or inches; others are downthrows of several thousand yards. Between these extremes all gradations are met with.

has the effect of producing a lateral displacement or **heave**—the amount of which is determined by the hade and the throw. For example, the truncated end of the coal-seam *a* (Fig. 33) is removed laterally by F^1 from its disconnected continuation a^2 by the distance *a—x*; but it is obvious that this distance would be increased if the amount of downthrow were augmented. Again, with the more gently inclined fault (F^2), the lateral displacement or *heave* is considerably increased. In the case of the vertical fault (F) there is, of course, no heave or lateral displacement. The inclination of faults, therefore, is of great importance in a coal-field, for the further the hade deviates from the vertical the wider will be the extent of "barren ground" between the two ends of a dislocated coal-seam.

The faults shown in the diagrams are straight lines, but in reality faults are not always or even often so smooth as they are here represented to be. Although the walls of a fault may be in close apposition, they are often separated either continuously or at irregular intervals by masses of jumbled and shattered rock-débris, known as **fault-rock** or **fault-breccia** (Plate XXXIX.). In many cases, also, cavities occur along a line of dislocation, and these are often filled or partially filled with crystallised minerals, as will be shown more particularly when we come to consider the phenomena of lodes or metalliferous veins. The walls of a fault and the stones in a fault-breccia are frequently slickensided, and afford other evidence of friction and crushing—the rocks along one or both sides being sometimes comminuted or pulverised for some inches or even for many feet back from the dislocation. Phenomena of this kind occur chiefly in connection with the more powerful faults—those, namely, which have produced the greatest amount of vertical displacement. In the neighbourhood of such large faults the rocks are not only broken and jumbled, particularly on the downthrow side, but on the same side strata are frequently turned up more or less abruptly against the dislocation. On the high side of the fault there is usually less disturbance and distortion, although the rocks tend to be bent over as if they had been dragged downwards in the direction of displacement. The annexed sections (Figs. 35, 36) will suffice to illustrate these appearances.

As a general rule, normal faults are more or less closely related to the leading or dominant rock-foldings of the district in which they occur. Hence they can usually be described as **Dip-faults** and **Strike-faults**, in this respect recalling the systematic arrangement of the joints characteristic of sedimentary strata. It must not be supposed, however, that the coincidence of faults with dip and strike is always close. The most that can be said is that they trend approximately in those directions. Frequently, however, they traverse the rock-folds obliquely, just as joints do, and sometimes it is difficult to detect any system or arrangement among them. Nevertheless, the larger faults tend, on the whole, to coincide more or less closely with the geological structures referred to—a relation which can hardly be said to characterise the smaller or less important dislocations. In these and other respects, therefore, normal faults have many analogies with the joints of sedimentary accumulations.

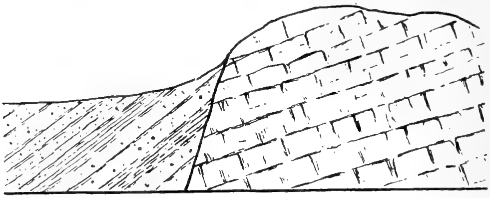


FIG. 35.—NORMAL FAULT, NOT ACCOMPANIED BY DISTORTION.

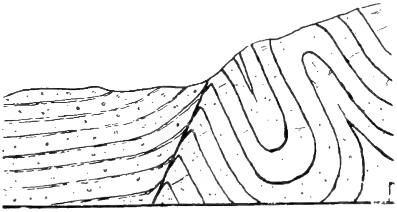


FIG. 36.—NORMAL FAULT, ACCOMPANIED BY DISTORTION.

Dip-faults have a characteristic effect upon the outcrops of rocks, which they appear to shift. This is well seen when such a fault crosses an escarpment, the long line of which is suddenly interrupted and shifted forward or backward, according to the position from which we view it. This advance or retreat of the outcrops along a line of dip-fault must not be confounded with the lateral displacement already referred to as the "heave" of a fault. It is the degree of inclination or "hade," and the amount of downthrow that determine the extent of lateral displacement, or "heave." A dip-fault, if vertical, produces no heave; but whether vertical or inclined, it never fails to cause an apparent horizontal shift of the outcrops—either forward or backward—according to the direction of downthrow. This apparent advance or retreat of faulted outcrops is greatest when the angle of dip is low, diminishes in proportion as the dip augments, and ceases altogether when the beds are vertical. The shifting, however, is not the result of any horizontal movement along the line of dislocation, but is simply the effect produced by denudation, as a glance at the models in Fig. 37 will show. Let A represent a block of strata dipping in one determinate direction. A dislocation, we shall suppose, takes place along the interrupted line *f f*. In B we have the same model showing the vertical displacement effected. A line dropped from the truncated end of the bed *a* to its disconnected continuation a^2 is a perpendicular—in other words, the fault is a vertical displacement. Now let us suppose that the surface is cut even by denudation along the line *s s*. The portion above this line we remove, and we have in C a ground-plan of the new surface thus produced. It now becomes evident that the horizontal shift is only apparent, and is simply the result of the removal of strata from the high or "upcast" side of the fault.

When dip-faults traverse anticlinal and synclinal folds, they necessarily cause similar apparent horizontal shifting of outcrops. But as the outcrops are shifted by one and the same fault in different directions, it is obvious that this effect cannot be the result of horizontal movements. This is made clear by the models in Figs. 38, 39. In Fig. 38, A represents a block of strata arranged in the form of a syncline which is eventually fractured along the line *f f* and displaced as shown in B. When the strata on the high side of the fault have been removed by denudation, and the whole area has been reduced to the same level *s s*, the outcrops will exhibit the appearance shown in C. It is evident, therefore, that a fault traversing a syncline has the effect of causing a mutual approach of the outcrops on the high side, and a correspond-

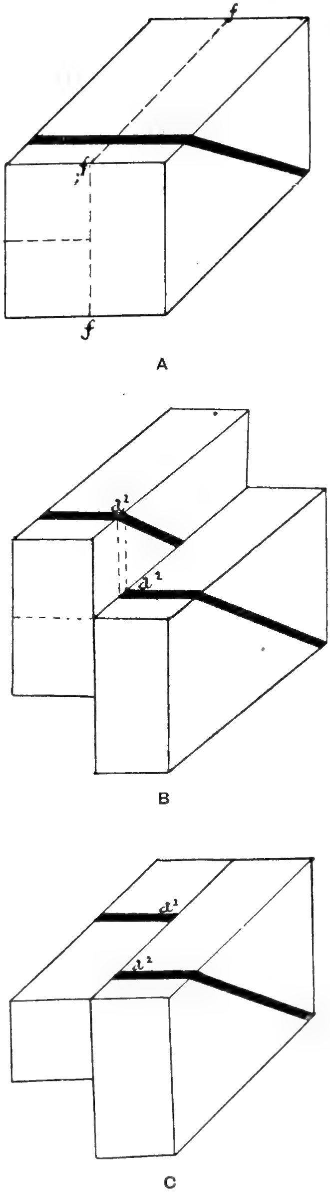


FIG. 37.—EFFECT PRODUCED ON OUTCROPS BY DIP-FAULT.

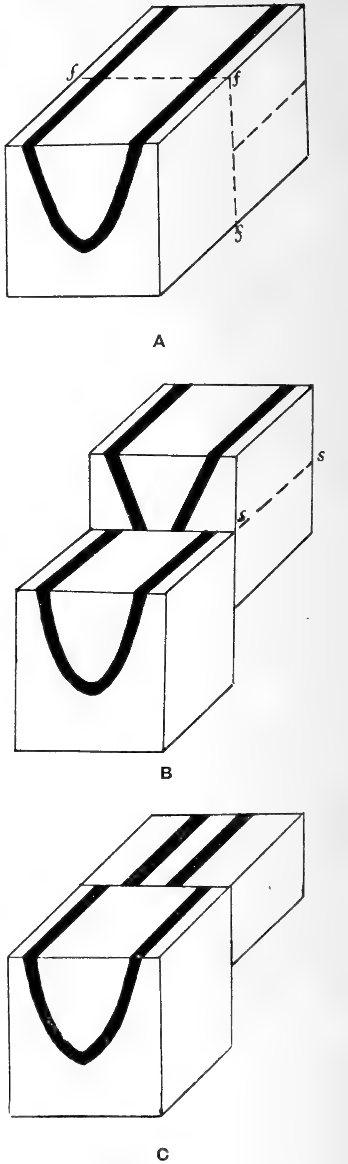


FIG. 38.—EFFECT PRODUCED ON OUTCROPS BY DIP-FAULT TRAVERSING SYNCLINAL STRATA.

FAULT-ROCK, RIVER GARRY, AT DALNACARDOCH, PERTHSHIRE.

Photo by H.M. Geological Survey.

[*To face page* 160.

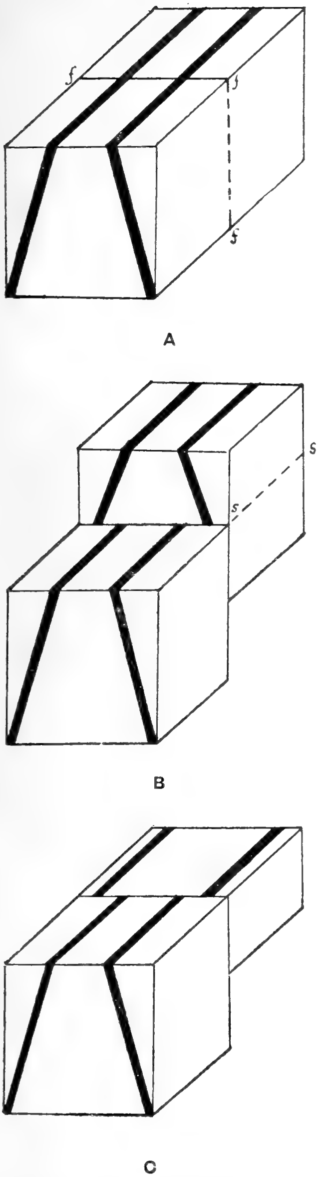


FIG. 39.—EFFECT PRODUCED ON OUTCROPS BY DIP-FAULT TRAVERSING ANTICLINAL STRATA.

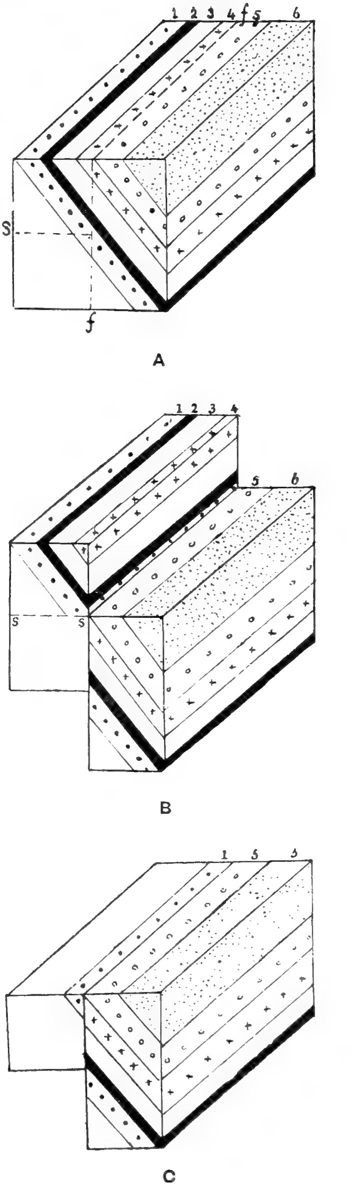


FIG. 40.—EFFECT PRODUCED ON OUTCROPS BY STRIKE-FAULT WITH DOWNTHROW IN THE DIRECTION OF DIP.

ing retreat of the outcrops in the opposite direction on the low side of the dislocation. Similar appearances present themselves when a fault cuts across an anticline, as will be seen by examining the models in Fig. 39. The anticline before dislocation is represented by A, while B shows the dislocation completed. When the portion lying above the line *s s* is removed, we have the new surface (C) produced by denudation, upon which the outcrops on the high side of the fault appear to have been shifted, but in opposite directions to the apparent shifting produced on the high side of a fault traversing a syncline. In the case of a faulted anticline the opposing outcrops on the "upcast" side appear to recede from each other, while on the "downcast" side the corresponding outcrops seem to have been brought closer together, the appearance of movement in opposite directions being, of course, entirely the effect of denudation.

Strike-faults or, as they are often termed, *longitudinal faults*, are so called because they trend in the general direction of the strike or the axes of the folds of a district. They also affect the outcrops, but in a different way from dip-faults. They do not cause any apparent horizontal shifting, and therefore are not so easily detected, in many cases at least, as ordinary dip-faults. Sometimes their downthrow is in the same direction as the inclination of the strata; at other times it is in the opposite direction or against the dip. In Fig. 40, A represents, as before, a block of strata traversed by a strike-fault *f f*, the vertical displacement being shown in B. In this case the *downthrow of the fault is in the direction of dip*. Removing the higher portion of the model above the line *s s* in B, we have the ground-plan as shown in C. Obviously, the effect of a fault hading in the direction of dip is to cut out strata—to carry their outcrops below the surface. In the area represented by the model A, we have a considerable succession of strata numbered consecutively, 1, 2, 3, 4, 5, 6. The same beds are shown in C, but some no longer crop out at the surface, but under the surface and against the dislocation. The beds 2, 3, and 4 are cut out, as it were.

Let us now take the case of a strike-fault which has a *downthrow against or in the opposite direction to the dip* of the strata. The effect of such a fault is precisely the reverse of that just described. Instead of cutting out strata at the surface, it causes outcrops to be repeated. A glance at the models (Fig. 41) will explain how that happens. In A we have the strata before displacement is effected along the line *f f*. B shows the dislocated strata, and in C we have the effect produced at the surface by the removal of the block projecting above the line *s*—the truncated ends of the beds 1, 2, and 3, being brought up, as it were, and caused to crop out again, so as to present the deceptive appearance of six beds all dipping in the same direction.

Strike-faults are apt to be overlooked when they coincide more or less closely with the line of bedding. An observer, for example, who should traverse either of the areas represented in the models C, C (Figs. 40, 41), might easily fail to detect any evidence of dislocation, and might be led to suppose that he had passed across continuous successions of strata; and thus, in the one case, he would assign too small, and in the other too great, a thickness to the series. It is rarely, however, that a fault follows the strike continuously; more usually it undulates from one side to another, and whenever it leaves the strike its presence is at once betrayed by the more or less abrupt truncation of the strata which it produces. But even when it keeps closely to the line of strike, variations in the amount of its downthrow will nevertheless indicate its presence. As will be shown presently, the throw of every fault necessarily varies. Each begins at zero—then gradually or more rapidly, as the line of fracture is followed, the downthrow increases until its maximum is reached, after which it diminishes until zero is again reached at its farther extremity. In other words, the crust is cracked along a certain line, and sinks or sags on one side of that line—the depression being greatest, as a rule, at a point midway between the two ends of the rent. The effect of a strike-fault with such a diminishing or increasing downthrow is illustrated by the models (Fig. 42). As in preceding illustrations, A represents the strata before displacement along the line *f f* has been effected. In B the fault has taken place, the downthrow being at a maximum at *x*, but gradually diminishing towards *z*, where it dies out. When the portion projecting above *s* is removed,

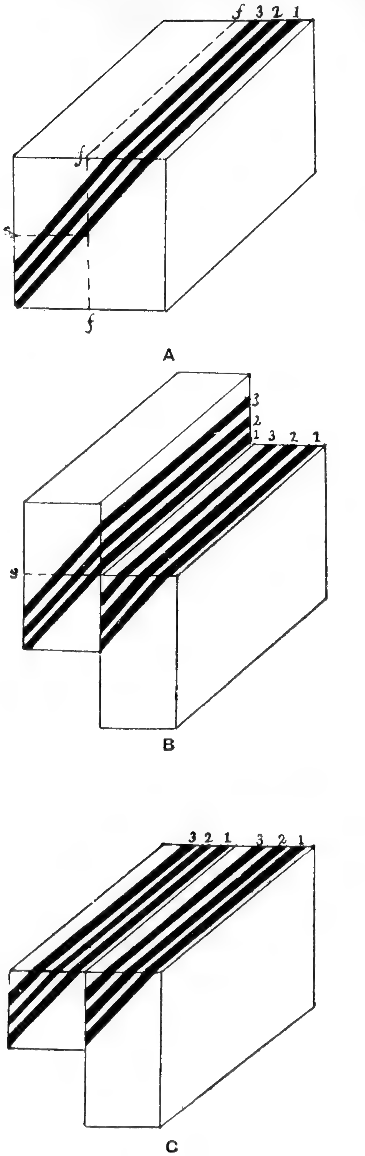


Fig. 41. — Effect produced on Outcrops by Strike-fault with Downthrow against the Dip.

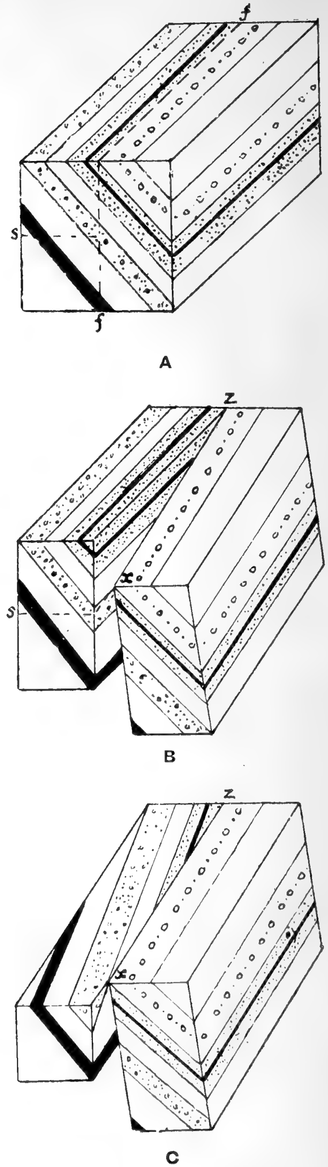


Fig. 42. — Effect produced on Outcrops by Strike-fault with a diminishing Downthrow.

we have the appearance shown in C, which represents the surface produced by denudation. It will be observed that upon the upcast or high side of the fault lower beds successively appear as the fault is followed from *z* to *x*.

Oblique Faults.—The effects produced by normal dip-faults and longitudinal or strike-faults are so marked that the one kind of fault cannot be confounded with the other. Dip-faults, however, do not always or even often traverse the outcrops at right angles, nor do longitudinal faults invariably keep to the line of strike. Oblique dip-faults and oblique strike-faults are of common occurrence, and occasionally the obliquity of a fault becomes so great that the dislocation cannot be properly termed either a dip-fault or a strike-fault. In Fig. 43, for example, A represents a coal-seam dipping due north, cut at an angle of 45° by a fault having its downthrow towards the north-east. It is obvious that this fault behaves partly as a dip-fault, inasmuch as it produces apparent horizontal shifting of the strata, and partly as a strike-fault, for it cuts out a portion of the outcrop. The fault represented in A^1 traverses a coal-seam at a more acute angle, and thus has rather the character of a strike-fault than a dip-fault, for

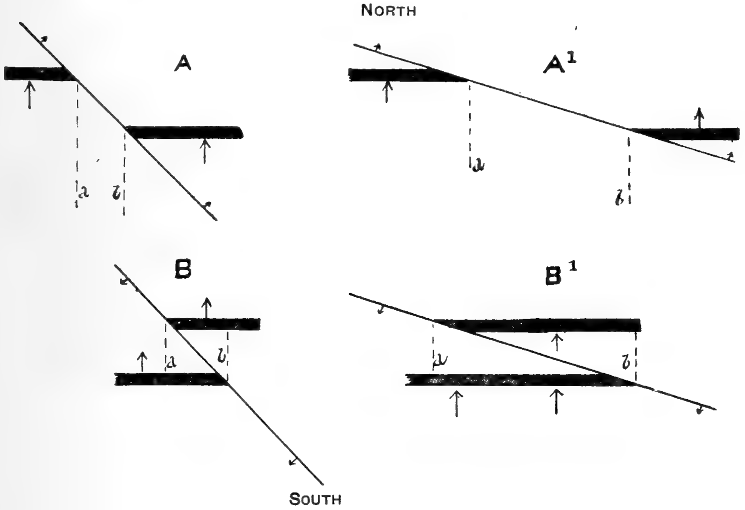


FIG. 43.—EFFECT PRODUCED ON OUTCROPS BY OBLIQUE FAULTS.

it cuts out a much larger part of the outcrop. The faults represented in B and B¹ have downthrows in the opposite direction to those shown in A and A¹, but otherwise they resemble the latter in behaving partly as dip-faults and partly as strike-faults. It will be observed, however, that the downthrows are in an opposite direction. In B, for example, a coal-seam is represented, as before, dipping due north, and intersected by a north-west and south-east dislocation hading towards south-west. The fault produces the effect of a dip-fault by shifting the outcrop, but since it crosses the strike obliquely it causes a duplication of the outcrop between *a* and *b*. The fault shown in B¹ approximates much more closely to the strike, with the necessary result that a longer stretch of outcrop is repeated. These diagrams should be compared with the models shown in Figs. 37, 40, and 41. From a study of the latter it becomes evident that the effects produced by the fault in A¹ more closely resemble those caused by the strike-fault C (Fig. 40), than those that result from the normal dip-fault C (Fig. 37). Again, the most notable feature in the diagram B¹ is the duplication of the outcrop—the fault having, for some considerable distance, the effect upon the outcrop of a strike-fault with downthrow against the dip (Fig. 41).

Groups of Faults.—Although faults often occur singly, more particularly when their throw is small—yet they frequently form associated groups or systems. Great dislocations, for example, which often extend for long distances, are rarely unaccompanied by parallel faults having downthrows in the same or opposite directions. Sometimes these parallel dislocations are so numerous and occur so closely together that it is often hard to say which is the main or principal fault. When the downthrow of all or most of them is in the same direction, the result is practically the same as if there had been only one dislocation with a large downthrow (see Fig. 44). Successive parallel strike-faults having their downthrows in one direc-

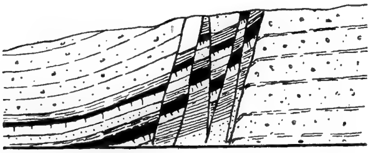


FIG. 44.—COMPLEX FAULT.

tion, or with some in one direction and some in another, often occur in our coalfields, where they are known as **step-faults**—an appearance shown in the diagram (Fig. 45). Such faults, when their downthrow is in the same direction as the dip, have the effect, as already indicated, of preventing certain beds from croping out at the surface. On the other hand, a succession of step-faults, each with its downthrow against the dip, may cause a coal-seam to crop out again and again. (See Fig. 46, which should be compared with the models in Fig. 41.)

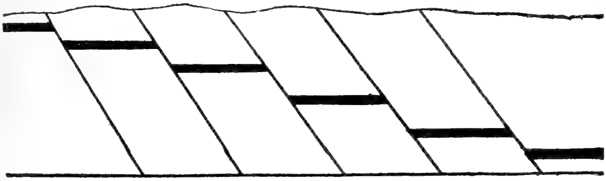


FIG. 45.—STEP-FAULTS.

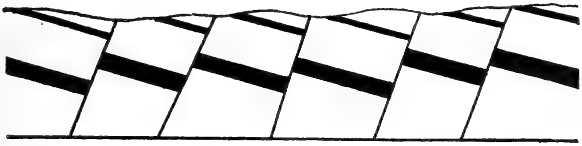


FIG. 46.—STEP-FAULTS HADING AGAINST THE DIP.

When parallel or approximately parallel faults hade towards each other, they produce the phenomena of **trough-faults** (Fig. 47, *t t*). When they hade away from each other

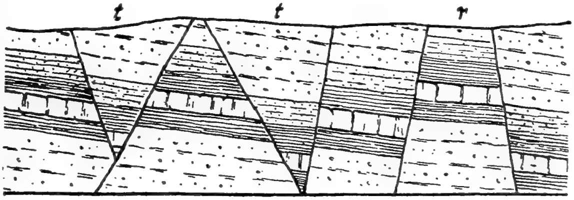


FIG. 47.—TROUGH-FAULTS AND RIDGE-FAULTS.

the converse structure appears (Fig. 47, *r*) for which there is no name in English.*

Faults having the same trend, but with their downthrows in different directions, often coalesce, and either suddenly terminate at the point of junction, or one may die out and the other continue with usually a diminished throw. But when approximately parallel faults, having their downthrows in one and the same direction, come together, they almost invariably continue as a single fault, often with an increased amount of downthrow.

The amount of throw of normal faults is, as we have seen, very variable—not exceeding a few feet in some cases, while in others it may reach thousands of yards, and thus bring into juxtaposition rocks of vastly different ages. The smaller faults usually extend for very short distances, while the greater ones may continue for hundreds of miles. The course of a large fault is usually approximately straight or gently sinuous, but not infrequently it is curved. Such faults may begin as a mere crack, or as a series of two or more converging fissures, with little or no accompanying rock-displacement. But as it continues, the throw gradually augments until a maximum is reached, after which it usually decreases until finally the fault dies out as it began—in a mere crack or series of cracks. In many cases, however, the throw varies very irregularly from point to point.

The phenomena presented by the two conjugate systems of **strike-faults** and **dip-faults** which are so characteristic of many regions, lead to the belief that these faults are of the same age—that they came into existence contemporaneously. This is suggested by several considerations to which reference will presently be made. But it may be pointed out here that strike-faults of contemporaneous age rarely or never cross each other; and the same is the case with dip-faults belonging to one and the same period of disturbance. One fault may, and often does, run into another, but it coalesces with it, and does not diagonally intersect it. When strike-faults are more powerful than the dip-faults of

---

* If one were required, perhaps **ridge-faults** might serve; but there are already so many superfluous geological terms that one hesitates to add to the number.

the same district, which is usually the case, the latter are intercepted by and do not cross the former. And similarly, when the dip-faults are stronger than the strike-faults, they cut these off.

Shifting of Faults.—This latter rule is so general, that when we find one fault crossing and shifting another, we may reasonably suspect that the two faults belong to different periods of disturbance. The relative age of intersecting faults is at once revealed by the fact that the younger dislocation shifts the older, just in the same way as any fault displaces strata. The phenomena are illustrated by the diagram (Fig. 48), where *a a* is obviously the older fault since it is displaced by the other (*b b*).

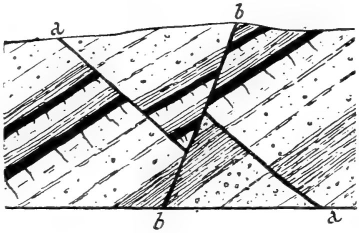


FIG. 48.—SHIFTING OF ONE FAULT BY ANOTHER.

Displacements of this kind are of common occurrence in much-disturbed regions, and prove that such areas have been rent and dislocated at separate—often widely separate—periods. In countries where ore-bearing veins are well

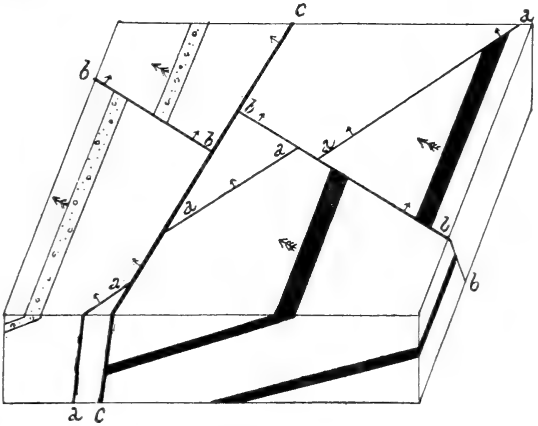


FIG. 49.—INTERSECTING FAULTS.

The feathered arrows indicate dip of strata; the small arrows show downthrow side of faults.

developed, these frequently occupy lines of dislocation, which intersect at various angles. In such regions, therefore, the direction or trend of conjugate systems of faults and their relation to other similar systems have been very carefully studied, and we now know that the dislocations of a region may belong to two, three, or more periods of crustal disturbance. In Fig. 49 we have a model showing three lines of faulting, of which it is obvious that the dislocation *a a* must be the oldest, since it is shifted by the fault *b b*; while the latter in its turn is shifted by the fault *c c*, which, therefore, must be the latest of the series.

REVERSED FAULTS.—These faults are so termed because the hade is not in the direction of downthrow, as is the case with normal faults, but in the direction of upthrow. Lower or older rocks on one side of the dislocation have been thrust up over higher or younger rocks on the other side. The hade of a reversed fault, especially if it be a great displacement, is usually further inclined from the vertical than the hade of a correspondingly large normal fault. In some cases, indeed, an extensive reversed fault approaches horizontality. The rocks along the line of a reversed fault are often much compressed, crushed, and broken. Not infrequently, indeed, such a fault is marked throughout its whole extent by a band of shattered and crushed rock, forming what is termed a *crush-* or *friction-breccia.** The rocks in the immediate proximity are also often more or less metamorphosed.

The most notable reversed faults are met with in largest numbers in regions of highly folded and compressed rocks. They are of comparatively rare occurrence amongst horizontal and gently inclined strata. Like normal faults, they frequently bear an obvious relation to rock-folds, and their phenomena will be better understood if considered in connection with the general question of the origin of faults.

TRANSCURRENT FAULTS OR TRANSVERSE THRUSTS.—It has been explained that the apparent horizontal shifting produced by normal faulting is really the effect of denudation. Horizontal shifting of outcrops on the large scale,

---

* If the stones are subangular or somewhat rounded, the fault-rock is sometimes termed *crush-conglomerate.*

however, does actually occur in certain regions of highly folded strata. Faults of this kind are steeply inclined or vertical, and often extend for many miles, always traversing the strata at approximately right angles to the strike. They are neither downthrows nor upthrows, movement having taken place in a forward direction, so that the walls of the thrusts are slickensided horizontally. Not infrequently the rocks on either side are much crushed and shattered, or the two walls may be separated by a "friction-breccia." Among the best-known examples of such transverse thrusts or transcurrent faults are those met with in the Alps and the Jura and in the Scottish Highlands.

Origin of Faults.—Although we have yet much to learn as to the origin of faults, there are certain conclusions which seem fairly well established. From our descriptions of the phenomena of **normal faults**, the student has doubtless gathered that these displacements are most satisfactorily explained by the view that they are true downthrows and not upthrows. Their somewhat constant relation to the dominant folds of a region seems to suggest that they are, like many joints, the result of torsional strain. We may suppose that the rents were produced or commenced at the time the strata were being folded. But folding implies, of course, lateral compression, and it does not seem likely, therefore, that the fractured rocks could subside so long as compression continued. When this movement had ceased, however, the bulged-up crust, relieved from lateral pressure, would tend to sink again, and subsidence would naturally take place along the cracks and fissures which had already come into existence. The whole area we may think of as being split up into a series of rectangular blocks of varying size, each block defined by fissures, some of which would be inclined in one direction and some in another. In this way a long rectangular block defined by two parallel strike-faults inclined towards each other, would have a relatively narrow base; while the adjoining block, defined by two parallel strike-faults inclined away from each other, would have a relatively broader base. Thus, when gravitation came into play and the fractured rock-masses commenced to sink, those with a relatively narrow base (presenting as they would a smaller area to pressure) would tend to sink more readily than the broader based segments that adjoined them. In short, downthrow would take place in the direction of the hade. It must be noted, however, that some amount of lateral pressure would be exerted by the several subsiding masses, which might now and again result in local distortion, crushing, and fracturing, such as so frequently accompany normal faults. This lateral pressure would also account for the fact that now and again the rocks on both sides of these faults are turned or bent upwards or downwards (see Fig. 50).

Apart, however, from any theoretical explanation of **normal faults**, we have direct evidence to show that such faults are occasionally so intimately connected with folds and flexures that we can have no doubt that they are contemporaneous, and due to one and the same crustal movement. Again and again, for example, large strike-faults, when traced continuously, have been found to die out in a flexure. In the case of monoclinal flexures it is not hard to see how that should be. Strain or tension must be set up along the margin of a sinking area. If subsidence should take place within a region built up of horizontal strata, the horizontal position of the rocks along the boundary or margin of the sinking area will be interfered with. The pull or drag of the descending mass will cause the strata of the adjacent stable area either to bend over or to snap across. Should the movement be slow and protracted, the rocks will probably at first yield by bending. They will be turned downwards and compressed, it may be, by stretching. But should the movement continue, they must eventually give way, and a fold will thus be replaced by a fracture. Towards one or both ends, therefore, we should expect such a fault to die out into a simple flexure or monocline (see Fig. 51).

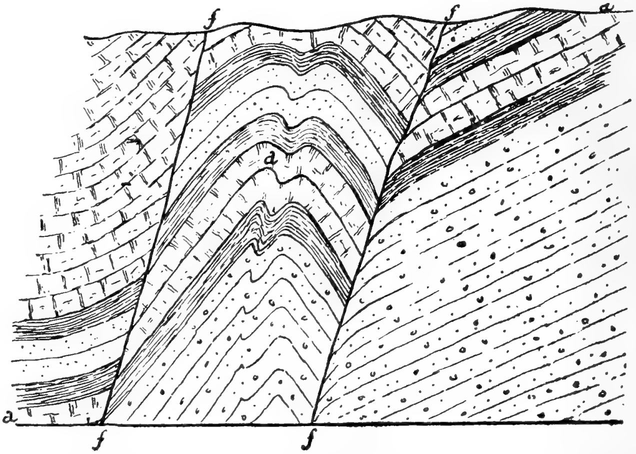


FIG. 50.—PARALLEL FAULTS WITH DISTORTED STRATA BETWEEN.

Although faults of the kind described may be considered the result of direct subsidence, it is obvious that they might equally well have resulted from movements of elevation. During the slow uplifting of a broad plateau, tension will come into play along the margin of the rising area. Flexures will then be formed, and these will eventually be replaced by rents and dislocations. The resulting structure would thus be the same as if folding and faulting had been caused by a movement of subsidence. Thus, in Fig. 51, the fault *f* might have been caused either by the subsidence of the strata at *x*, or by the upheaval of the strata at *a*. But as the dominant movement of the earth's crust must be one of subsidence, it is preferable to consider all normal faults as downthrows rather than upthrows. Nevertheless, our knowledge of the nature of crustal movements is not so complete that we can deny the possibility, or even the probability, that normal faults may now and again have come into existence during movements of upheaval.

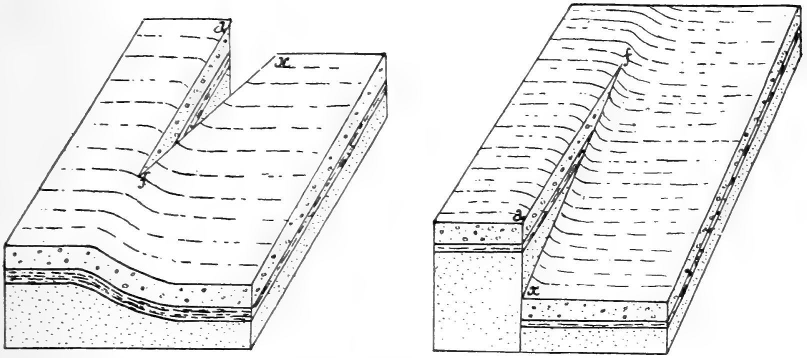


FIG. 51.—MONOCLINAL FLEXURE PASSING INTO A NORMAL STRIKE-FAULT, VIEWED IN OPPOSITE DIRECTIONS.

(After Chamberlin and Salisbury.)

Reversed faults do not often occur in regions where the rocks show little trace of disturbance. This seems to be due to the simple fact that they are the result of lateral pressure or compression, so that they are best developed and of most common occurrence amongst highly folded and distorted rocks. Now and again, however, where monoclinal flexures have obviously resulted from horizontal movements, the flexures have yielded and given place to reversed faults (see Fig. 52). In other cases gently inclined strata, when subjected to lateral pressure, have, instead of first folding, at once yielded to the strain by snapping obliquely—and one portion of the severed mass has been pushed bodily

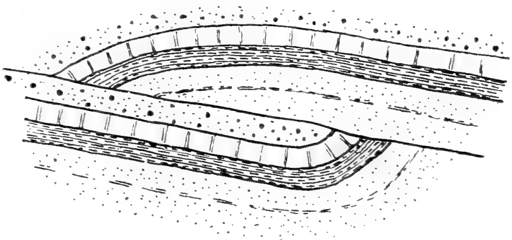


FIG. 52.—REVERSED FAULT REPLACING MONOCLINAL FLEXURE.

over the other. But faults of this kind, occurring in gently inclined strata, are usually on a small scale, and merely of local importance.

One of the commonest kinds of reversed fault is that known as an **overthrust**. All folds, as we have seen, are the result of horizontal movement or tangential pressure. When this is excessive, folds are rendered more and more unsymmetrical, the middle limb of each fold becoming thinner and thinner as the rock is drawn out in the direction of movement. With continued pressure the limb at length yields, and the highly inclined or recumbent anticline is pushed forward—in short, the fold is dislocated and a reversed fault comes into existence. All gradations of such overthrusts may be studied in most regions of highly folded and contorted strata (see Fig. 53). So overpowering has been the horizontal movement in some cases, that masses of rock thousands of feet in thickness have been buckled up and sheared. In other cases, however, great reversed faults have been produced without much preliminary buckling or folding of the rocks. Many remarkable examples of this kind occur in the north-west of Scotland. In that region sheet after sheet of rock has been successively sliced off and driven forward, sometimes for ten miles or more, so that the oldest rocks often overlie the youngest rocks (see Plates XL., XLI.).

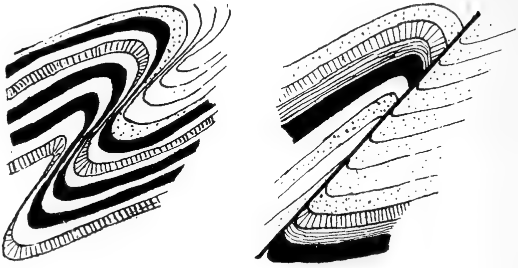


FIG. 53.—ORIGIN OF REVERSED FAULTS IN HIGHLY FOLDED ROCKS.

Plate XL. is a view of Sgurr Ruadh, a mountain in Ross-shire. It shows the north face of the mountain along which the following series of bedded rocks crop out:—*a*, Torridon Sandstones; *b*, Basal Quartzite; *c*, Pipe-rock. The white lines are thrust-planes which traverse the hill-face in the same direction as the outcrops. Plate XLI., for which I am indebted to my old colleague and friend, Dr Peach, is a section taken obliquely across the mountain, and shows the general structure of the ground. From the base of the mountain up to the first thrust-plane the strata occur in their true order; thereafter, it will be seen they are inverted, and have been driven forward. The two thrust-planes which appear in section on the hill-face are branches of one and the same overthrust, as is shown in the section. The thrust-planes of the north-west Highlands are inclined at various angles, but the larger ones usually deviate most from the vertical. Not infrequently, indeed, they are almost horizontal. In the general

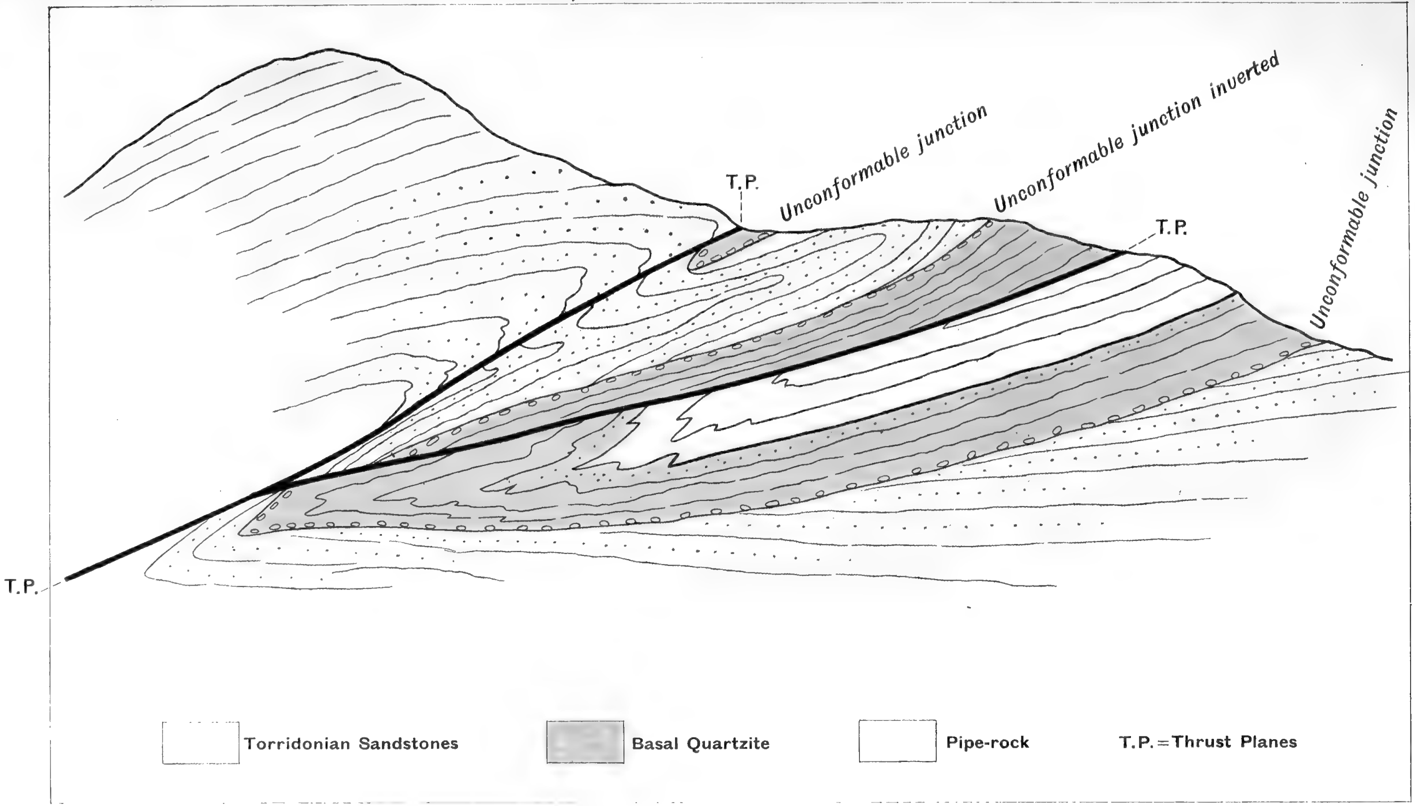
PLATE XL.

North Face of Sgurr Ruadh, Achnashellach Forest, Ross-shire. White lines show edges of Thrust-planes.

Photo by H.M. Geological Survey.

To face Plate XLI.]

SECTION ACROSS SGURR RUADH, SHOWING INVERSIONS AND THRUST-PLANES (*B. N. Peach*)



[*To face Plate XL.*

denudation of the country these thrust-planes have now and again given rise to marked surface-features. As lines of weakness, for example, they are sometimes followed by streams—a good instance being shown in Plate XLII.

Transverse thrusts are obviously due to the same cause as overthrusts—tangential pressure,—and may be looked upon as contemporaneous with the folds and overthrusts of the region in which they occur. When the strata of a growing mountain chain were being compressed and pushed forward in some particular direction, there might well be inequalities in the crustal creep. Some portions of the moving mass would advance more rapidly than others, and thus cause strain and tension, to which the crust would necessarily yield in the direction of the horizontal movement. The vertical fissures and fractures or glide-planes thus formed would, therefore, traverse the dominant folds and overthrusts of the chain at right angles.

The general conclusion, then, to which the evidence leads is simply this, that faults are usually connected with folds, or, at all events, with horizontal movements of the crust. When strata are sufficiently compressed, they usually double up, and with continued pressure eventually yield, and overthrusts take place. In some cases, however, in place of becoming folded, they at once shear, and approximately horizontal or steeper overthrusts come into existence. Again, yielding takes place, and transcurrent faults make their appearance between contiguous masses which are moving horizontally at different rates in the same direction.

The overthrusts of a highly disturbed region are often cut across by a series of normal faults, and such phenomena seem to suggest that, while overthrusts and transverse thrusts are the result of horizontal movements, the normal faults in question may have come into existence when the tangential pressure was relieved. During a great horizontal movement, the rocks are not only subjected to enormous compression, but the crust is bulged up—in other words, mountains of elevation are formed. When the forward movement ceases and pressure is relieved, the protuberant rock-masses will tend to settle down to some extent along the rents and fissures opened during the elevatory process, and normal faults will thus be produced. In the case of normal faults traversing horizontal and gently inclined strata, all we can say is that, like joints, they probably owe their origin to torsion, and since they are so commonly related to strike and dip, it seems highly probable that they also are the direct result of crustal folding. But we must not forget that many normal faults have been formed during movements of direct subsidence—which may not necessarily have been connected with any horizontal movements of the crust. Not a few extensive basin- or trough-shaped depressions are bounded by normal faults, and are obviously the result of direct subsidence or collapse of the crust.

Crustal deformation would appear usually to have been slowly effected. Under sufficient pressure solids can be compelled to flow, and hard rocks may be bent without fracturing, provided the pressure be applied gradually.

It is impossible to believe that the folded strata seen in a mountain range could have been so sharply curved and plicated without fracture, unless as the result of powerful pressure slowly applied. As regards dislocations, there is no evidence to show that great rock-displacements have been more rapidly effected than conspicuous rock-folds. We need not go so far, however, as to infer that all faults have been slow creeps. Some dislocations may have been more or less rapidly effected. That crustal deformation, as a rule, is really a protracted process, is strongly suggested by the fact that folds and faults have come into existence in certain regions without disturbing their drainage systems. The Colorado Plateau, for example, has been split across by well-marked normal faults, some of which have a downthrow of several thousand feet, and can be followed for hundreds of miles. The same region also shows some notable folds and flexures, both faults and flexures being of relatively recent geological age. Yet none of these crustal deformations has disturbed the course of the River Colorado, which was certainly in existence long before they had been effected. It is obvious, therefore, that flexuring and faulting must have taken place so gradually, that the river was able to saw its way across the inequalities as fast as these appeared. Similar evidence to the same effect is supplied by the river-valleys of the Himalayas. It is well known that the sub-Himalayan ranges are composed of materials derived by existing rivers from the central ranges of the great chain. The materials referred to form massive accumulations which have been disturbed and upheaved, the axes of the flexures crossing the river-valleys more or less directly. Here, then, it is evident that "the rivers are older than the hills they traverse, and that the gorges have been gradually cut through the hills as they were slowly upheaved." Yet another example may be cited from our own Continent. Deep borings have shown that the Pleistocene deposits in the valley of the Rhine in Hesse occupy a profound hollow, surrounded on all sides by older rocks, the bottom of the basin being 270 feet deeper than the lowest part of its rim at Bingen. These deposits, however, are not lacustrine, but fluviatile. Hence we must infer that fluviatile deposition has kept pace with the crustal movement. As the bottom of the Rhine valley has slowly subsided, the river has flowed on without interruption, continuously filling up the gradually deepening basin with its sediment.

STREAM RUNNING IN LINE OF THRUST-PLANE, ALLT MOR, KISHORN, ROSS-SHIRE.

Photo by H.M. Geological Survey.

[*To face page* 176.

CHAPTER XII

STRUCTURES RESULTING FROM DENUDATION

Outliers and Inliers. Unconformity. Overlap.

IN preceding chapters, frequent reference has been made to denudation in explanation of certain constantly occurring phenomena. For example, it was necessary to point out that plutonic rocks are now visible at the surface simply because they have been bared or denuded by long-continued epigene action. The student who has followed so far must also have realised that the very existence of sedimentary rocks is evidence of denudation—for every bed of the kind has been derived from the breaking-up and disintegration of some pre-existing rock or rocks. Denudation and sedimentation, in short, go hand in hand. We cannot have the one without the other. In the sequel, we shall discuss the subject of denudation, with special reference to the surface-features of the land; but, for the present, attention must be confined to certain rock-structures which may be said to owe their origin to denudation.

Outliers and **Inliers.**—All land-surfaces are necessarily subject to degradation, and the marks of such degradation or wearing-away are necessarily most conspicuous in regions which have been longest exposed to epigene action. Vast masses of rock have been gradually removed from such regions, so that many formations which formerly extended continuously over wide areas have been greatly reduced. Sometimes, indeed, they are now represented by only a few interrupted sheets and isolated patches. Such is the origin of outliers. An **Outlier,** then, is simply a relic of some more or less extensive bed, or series of beds, and may be shortly defined as a detached area of rock, surrounded on all sides by rocks which are geologically older than itself. Such being the case, outliers very often appear capping hills and ridges. They occur amongst all kinds of rocks, no matter how these may be arranged—whether they be horizontal, inclined, or highly flexed and folded. Examples are met with almost everywhere throughout these islands. They often appear scattered along the front of prominent escarpments, of which they are really the outposts, as may be seen in Fig. 54, which represents diagrammatically the outliers and escarpments of the Jurassic and Cretaceous strata of Central England. These outliers are obviously detached portions of the more durable strata, of which the escarpments are composed, and have been left behind, so to speak, during the slow retreat of the latter under the influence of denudation. Sometimes outliers owe their preservation not so much to the durability of their rocks, as to their relatively strong geological structure. Hence, not infrequently, outliers occur in synclinally arranged strata (Fig. 55, O). The rocks of which an outlier is composed may all belong to one and the same series, or the upper portion may rest discordantly upon the lower—showing that they belong to very different geological horizons (Fig. 55, O^1).

FIG. 54.—ESCARPMENT, E, AND OUTLIER, O.

Although outliers usually occur on high-lying ground as the direct result of denudation, yet they occasionally owe their existence to faults, and in such cases they may appear either on heights or in depressions. Trough-faults, for example, necessarily bring down younger beds against older formations, and thus detached portions of strata are preserved—the rocks with which they were formerly connected having been entirely removed from the immediate neighbourhood.

An **Inlier** is the converse of an outlier, and consists of rocks which are surrounded on all sides by rocks which are geologically younger. The rocks of an inlier may belong to the same geological series as those by which it is surrounded, or they may be overlaid discordantly by the latter (Fig. 55, I, I^1). As an inlier is the result of denudation, and due simply to the partial removal of overlying rocks, the structure is most frequently encountered in valleys and other depressions. Now and again, however, an inlier appears along the back of a denuded anticline, as in the case of the Carboniferous Limestone of Roman Camp Hill, near Edinburgh (Fig. 56, I). Faulting also sometimes accounts for the presence of an inlier forming elevated ground. For example, we occasionally encounter hills composed of ancient rocks rising more or less abruptly out of plains or plateaus consisting of younger formations. This is the structure of the "Horst mountains" of German geologists, the general characters of which are shown in Fig. 57. In this case it is obvious that

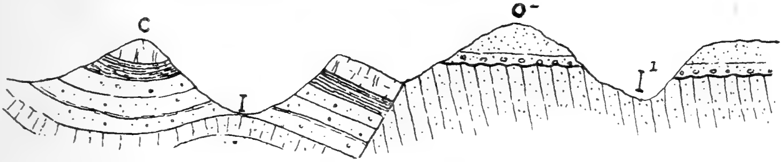


FIG. 55.—OUTLIERS (O) AND INLIERS (I) IN CONFORMABLE AND UNCONFORMABLE STRATA.

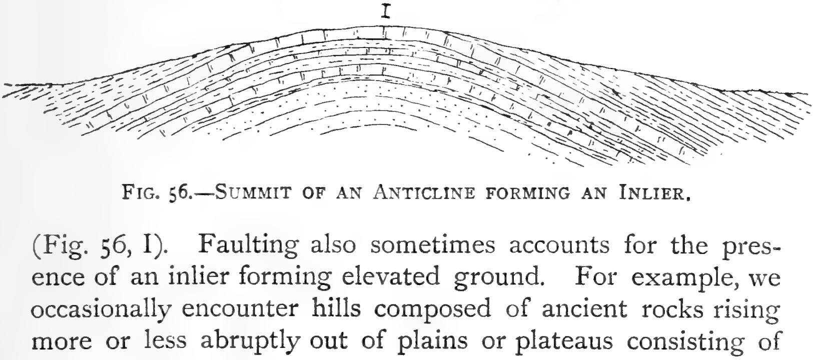


FIG. 56.—SUMMIT OF AN ANTICLINE FORMING AN INLIER.

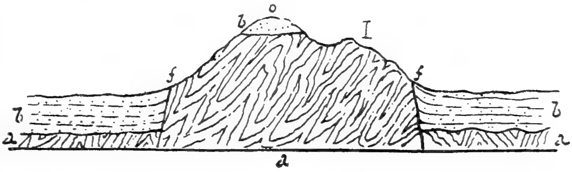


FIG. 57.—INLIER RESULTING FROM FAULTING.

a, schistose rocks; *b*, *b*, younger sedimentary strata; *f*, *f*, faults; *o*, outlier of *b*; I, inlier of *a*.

the inlier represents a higher crustal level—the Horst owes its existence as such to the faults or dislocations by which it is bounded. An old plateau-land has been fractured—the tracts surrounding the inlier having broken away from it, and dropped to a lower position.

Conformity and **Unconformity.**—When one series of strata has been laid down upon the undisturbed and undenuded surface of another series, so as to form a continuous succession, the beds are said to be conformable—the structure being known as conformability or conformity. In a true **conformity**, therefore, each successive bed rests regularly upon its predecessor. When, on the other hand, one set of beds has been deposited upon the worn or denuded surface of another and older series, we have what is termed an **unconformity** or unconformability, and the two sets of beds are said to be unconformable with each other. Unconformity sometimes occurs without any change in the relative position of the younger and older strata. Both may be horizontal, or may dip at the same angle and in one and the same direction (Figs. 58, 59). In such cases the lower series will usually afford evidence of having been more or less denuded before the deposition of the overlying series had commenced. Occasionally, however, such evidence of a physical break or

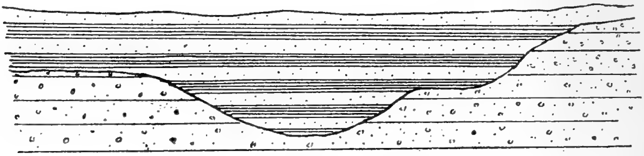


FIG. 58.—MARKED UNCONFORMITY IN HORIZONTAL STRATA.

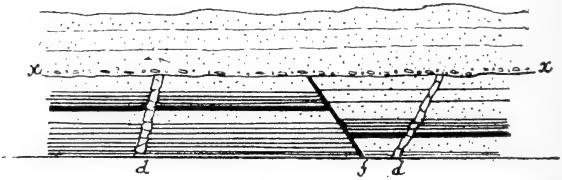


FIG. 59.—INCIDENTAL EVIDENCE OF UNCONFORMITY IN HORIZONTAL STRATA.

x, x, unconformable junction; d, d, dykes; f, fault.

interruption of sedimentation is hard to detect in individual exposures or sections. But when the strata are traced over some considerable area the actual discordance will be shown by the manner in which the upper gradually steals over the outcrops of the lower series. In cases of this kind the presence of an unconformity is often indicated by the occurrence of rolled or angular fragments of the lower rocks enclosed in the lowest bed or beds of the upper series. Indeed, conglomerate and grit frequently appear along every kind of unconformable junction. Again, the presence of dykes of igneous rock and dislocations in the lower series and their absence from the overlying beds—dykes and faults terminating abruptly at a given line of junction—would be convincing evidence of a "break in the succession" (see Fig. 59). For it is highly improbable that two or more dykes should terminate upwards at exactly the same level; while we may feel assured that if the dislocations visible in the lower beds do not extend into the overlying strata, the latter must be resting upon a denuded surface.

When none of these incidental proofs of unconformity is present, the evidence of fossils may yet be available. The assemblage of fossils occurring in the lower beds may be more or less strongly contrasted with that of the overlying series, and so lead to the conviction that the appearance of conformity is deceptive. Such an abrupt break in the continuity of life-forms is termed by palæontologists a "break in succession," and indicates a gap or imperfection in the record, which usually implies a long lapse of time. We must allow for the gradual extinction of the old forms of life occurring in the lower beds, and for the gradual introduction of the different series of types which appear in the upper beds. In short, the apparent conformity in such a case is deceptive—it is in reality an unconformity.

Usually, however, unconformity is marked by some discordance of inclination—one set of beds often resting upon the upturned and denuded edges of an older series (see Figs. 60, 61). Thus the lower beds may be inclined and the overlying strata horizontal; or both may be inclined in the same or in different directions. Strongly marked discordances of this kind are not hard to trace, even when there is no section to show the actual junction of the two sets of strata.

Conformity, as a rule, indicates more or less continuous sedimentation or accumulation—a persistence, upon the whole, of the same physical conditions. It does not, however, prove that the area of deposition was stable. On the contrary, a thick series of conformable strata of shallow-water origin could only have been accumulated during gradual subsidence of the area. The evidence supplied by palæontological "breaks in the succession," further shows that the accumulation of apparently conformable strata has sometimes been interrupted for prolonged intervals of time. But these are really cases of unconformity, and do not invalidate the general rule that true conformity indicates a persistence of the same physical conditions.

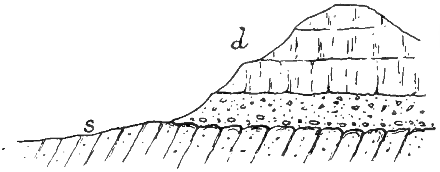


FIG. 60.—STRONG UNCONFORMITY.

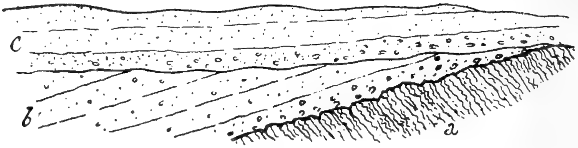


FIG. 61.—TWO UNCONFORMITIES.

It must be remembered, however, that conformable strata have not necessarily accumulated during one continuous movement of subsidence. As already pointed out (see p. 110), both downward and upward crustal movements may take place during the deposition of a long series of perfectly conformable strata, and these changes may sometimes lead to longer or shorter pauses in the process of accumulation. While, therefore, it holds generally true, that conformity is the result of more or less continuous sedimentation, we must allow for such interruptions of the process as those discussed in Chapter VII.

Unconformity, on the other hand, obviously implies an interruption of sedimentation or accumulation, and the supervening of erosion and denudation—or, in other words, a change of physical conditions. In short, unconformity points usually to the following succession of changes: (1) a period of accumulation—either lacustrine or marine; (2) a crustal movement resulting in the conversion of the area of sedimentation into dry land; (3) a more or less prolonged period of erosion, during which the land surface is denuded; (4) renewed subsidence and deposition of younger accumulations over the worn and irregular surface of the now drowned land; (5) final re-elevation of the area.

Overlap.—When the upper beds of a conformable series extend over a wider area than the lower beds of the same series, we have the structure known as overlap. The structure indicates subsidence accompanied by sedimentation over a gradually extending area, and overlap is therefore often well displayed in cases of marked unconformity. In the accompanying section (Fig. 62), for example, the older rocks, *a*, have been much eroded, so that when submerged they formed a very irregular sea-floor. The hollows being gradually filled with sediment, *b*, it is obvious that the upper must overlap the lower beds—each stratum extending over a wider area than its predecessors. But overlapping must take place in every case of the gradual subsidence of land, whether the surface of the sinking area be irregular or relatively smooth. As the land sinks, shore-deposits become overlapped by infra-littoral deposits, and these last by the accumulations of deeper water.

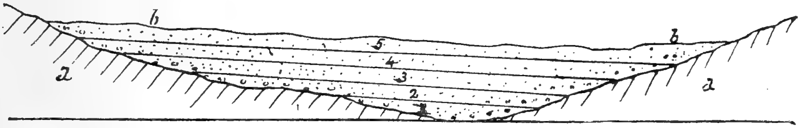


FIG. 62.—UNCONFORMITY AND OVERLAP.

Overlap is a structure which is not only interesting and instructive to the geologist, but it has also an obvious practical bearing. In questions of boring for bedded minerals it is often of the utmost importance, and failure to recognise the structure has led to disappointment and loss which might have been avoided. Similarly, in questions of water-supply, the possible occurrence of overlap and unconformity cannot be safely disregarded.

CHAPTER XIII

ERUPTIVE ROCKS: MODE OF THEIR OCCURRENCE

Intrusive Eruptive Rocks. Plutonic or Abyssal and Hypabyssal Rocks—their General Petrographical Characters. Batholiths—Granite as a type; phenomena along line of Junction with Contiguous Rocks; Xenoliths; speculations as to Assimilation of Rocks by Granite, etc. Laccoliths of North America. Sills or Intrusive Sheets appear to be much-denuded Laccoliths. Necks or Pipes of Eruption—their General Phenomena.

IGNEOUS rocks have either been extruded at the surface, as in the case of volcanic eruptions, or they have cooled and consolidated below ground, and are now exposed to the light of day owing to the removal by denudation of the rock-masses underneath which they formerly lay concealed. We have thus two types of eruptive rocks, namely, effusive and intrusive, the latter of which is most conveniently described first.

INTRUSIVE ERUPTIVE ROCKS

These rocks are sometimes termed **subsequent,** with reference to the fact that they are of subsequent origin to the rock-masses with which they are associated. Two groups of intrusive rocks are recognised, namely, **Plutonic** or **Abyssal** and **Hypabyssal** rocks, the former having consolidated at great depths in the crust, while the latter are of less deep-seated origin. It must be admitted, however, that no clear line of demarcation separates these two groups—the one type of rock passing into the other. Nevertheless, the extremes of the two series are more or less strongly differentiated by their petrographical characters, and also to some extent by the mode of their occurrence.

The Plutonic or more deeply seated rocks are never vesicular or slaggy, and contain no glass. Moreover, they are usually—not always—rather coarsely crystalline, and generally granitoid in texture. Their constituent minerals are often crowded with fluid-cavities, while glass- and stone-cavities are wanting. The Hypabyssal or less deeply seated rocks occasionally exhibit all these characters, but they also not infrequently contain sporadic areas of vesicles, and even, it may be, some residual glassy base or devitrified matter. Although often coarsely crystalline, they commonly assume a fine-grained and sometimes a compact texture. Hypabyssal rocks thus frequently have a strong resemblance to effusive or lavaform rocks, from which, indeed, it is often quite impossible to distinguish them in mere hand-specimens. The contrast between these two types is consequently much less marked than that between plutonic rocks and true lavas. Even in hand-specimens a truly plutonic or abyssal rock can rarely or never be confounded with one which has flowed out at the surface and consolidated under the ordinary pressure of the atmosphere.

The true character of an igneous rock, however, can only be satisfactorily determined by studying it in the field, and observing its relation to the other rock-masses amongst which it occurs. Usually it is not difficult to recognise an intrusive rock, since its junction with surrounding rock-masses is generally more or less irregular or discordant. Many observations in all parts of the world have shown that molten matter invading the crust from below has usually followed what may be considered lines of weakness. That crust, as we have now learned, is by no means homogeneous, but built up of a great variety of rocks arranged in many different ways, and traversed by an infinity of regular and irregular cracks, fissures, rents, and dislocations, many of which are vertical or approximately so, while others are inclined at all angles. All such original and superinduced planes of division—whether planes of bedding, cleavage, or foliation, whether unconformable junctions, joints, or faults—are lines of weakness along which molten matter has from time to time found more or less ready passage to the surface. Further, it may be noted that molten matter has not infrequently made a way for itself by fusing or dissolving and absorbing certain rocks, such as coal and limestone, and even much less readily reduced materials.

It is obvious, therefore, that molten masses which have cooled and consolidated within the earth's crust must vary in shape according to the form of the passages and cavities which have been opened for them. Consequently, from the point of view of tectonic geology, intrusive eruptive rocks are grouped under certain more or less definite structural types. It must not be supposed, however, that each individual intrusive mass necessarily belongs wholly to one or other of these typical structures. Not infrequently, as we shall learn, several different types may be represented by one and the same eruptive rock-mass. The more important structures recognised by geologists are as follows :—*Batholiths ; Laccoliths* and *Sills* or *Sheets ; Necks* or *Plugs ;* and *Dykes* and *Veins.*

I. BATHOLITHS

The term **Batholith** is applied to an intrusive mass, of deep-seated origin, which seems to occupy an amorphous or irregular shaped cavity, usually of large dimensions, often, indeed, measuring several miles in diameter (Fig. 63). Batholiths consist usually of some granitoid holocrystalline rock, as granite, syenite, diorite, gabbro, dolerite, etc. Occasionally, however, quartz-porphyry occurs in similar masses. But the most characteristic batholiths are unquestionably the deep-seated plutonic masses of granitoid holocrystalline rocks, of which granite itself may be taken as the type.

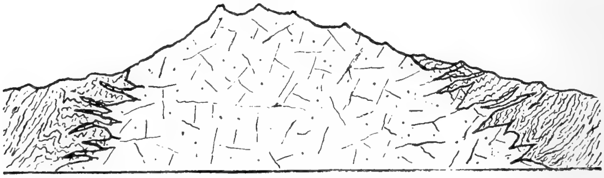
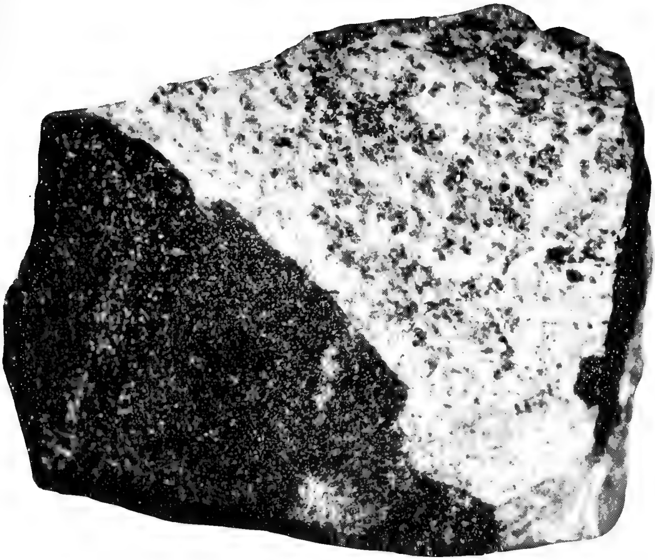
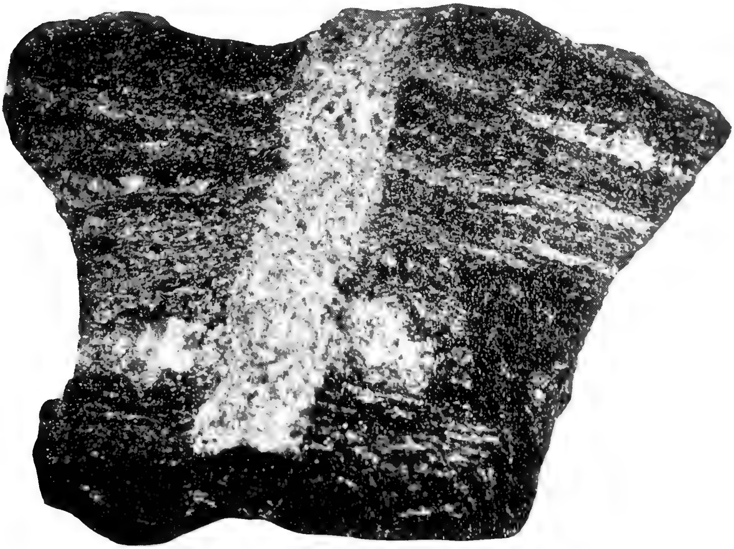


FIG. 63.—DIAGRAMMATIC SECTION ACROSS A BATHOLITH.

The petrographical character of granite, not less than the phenomena presented by the rocks it traverses, are sufficient proof of its deep-seated origin. Granitic intrusions range in age from the oldest period recognised by geologists down to



1. JUNCTION OF GRANITE WITH FINE-GRAINED GNEISS. Natural size.



2. VEIN OF GRANITE TRAVERSING GNEISS. Natural size.

[*To face page* 186.

Tertiary times. By far the larger number, however, date back to Palæozoic and Archæan ages—very few, indeed, being referable to Mesozoic and Cainozoic horizons. From this we are not justified in concluding that intrusions of granite were of more common occurrence in the earlier than in the later stages of the world's history. Granite, being of plutonic origin, can only appear at the surface as the result of long-continued and profound denudation, and its relative age is fixed by that of the rocks it traverses. If the surrounding rocks be of Palæozoic age, all we can say is that the intrusion is of later date than these—but how much later we cannot tell. For, obviously, much denudation must have taken place before the granite could become exposed at the surface. It may originally have risen to a much higher geological horizon—all evidence of this having been destroyed by the complete removal of the overlying younger rocks, and those portions of the batholith itself by which these may have been penetrated. As every granite intrusion must in this way have traversed older rocks before it could reach superincumbent younger rocks, we might have expected to find batholiths most frequently associated with the former, although many may really belong to a much later date.

Collateral evidence sometimes enables the geologist to fix the approximate age of a batholith. When, for example, the rock is seen traversing Carboniferous strata, while fragments of it are enclosed in beds of early Permian age, we may infer that the intrusion probably took place towards the close of Carboniferous times.

Along its junction with adjacent rocks, granite is often finer grained than elsewhere in the same mass, as if the molten magma had become chilled by contact with its surrounding walls, and cooled too rapidly to allow the constituent minerals to attain fuller development (see Plate XLIII. 1). Not infrequently, however, the rock is as coarsely crystalline along its margin as towards the centre of the mass. In such cases we may suppose that the surrounding rocks were so highly heated as to have no chilling influence. Although the junction between granite and the rocks invaded by it is usually so clearly defined that a knife-edge may be laid upon it, yet this is not always the case. Occasionally, the eruptive rock seems to merge insensibly into the other, and no line of demarcation is visible. Again, it sometimes happens that when granite has invaded schists or slates it has penetrated these by a kind of leaf-by-leaf injection — the liquid rock having insinuated itself in excessively thin sheets and veins along planes of foliation or cleavage. Under such conditions the invaded rocks are so intimately mixed with granite and so highly metamorphosed, that it is often very difficult to distinguish between them and the invading rock. The alternating leaves of granite and schist combine, in short, to produce a rock which has the aspect of a gneiss into which the granite-mass seems, as it were, to graduate.

Now and again the marginal area of a granitic batholith contains more or less numerous angular and subangular fragments, slabs, reefs, and blocks of schistose or other rocks. Such inclusions, or **xenoliths**, as they are called, are not to be confounded with the relatively fine-grained, dark basic secretions described in Chapter III., as characteristic of many granites. On the contrary, they have obviously been torn from the rocks abutting upon the granite and enclosed in it at the time of its intrusion. It may be added that granitic batholiths not infrequently show a kind of foliated or flow structure near their margins—the constituent minerals being arranged roughly parallel to the junction-line. This may indicate an actual fluidal movement, or it may simply be the result of hydrostatic pressure, exerted by the mass of the granite itself.

Batholiths are often rudely circular or elliptical in groundplan, and seem, in some cases, to rise up vertically, as if they occupied an enormous pipe or funnel. The rocks surrounding such batholiths have no appearance of having been thrust aside to make room for the intrusive mass. To explain this, it has been suggested that the rocks which formerly occupied the site of the batholith may have been melted up and assimilated by the granite. That absorption to some extent has actually occurred, in some cases at least, is suggested by the fact, already mentioned, that granite occasionally merges gradually into the rocks against which it abuts. It is further noteworthy, in this connection, that a difference of chemical composition has now and again been detected between the granite near its margin and towards the centre of the mass. It would seem, however, that xenoliths are confined as a rule to the marginal areas of a batholith, whereas, had the rocks which formerly occupied its site been broken up and absorbed, one might have expected to meet with occasional detached xenoliths throughout the whole mass, while the granite itself ought to have varied more or less markedly in composition, considering the very different kinds of rock-material which it must have absorbed. Granitic batholiths do, indeed, sometimes vary remarkably as regards their petrographical character: but such variations are cases of magmatic differentiation, and appear to be due to the way in which the mineral constituents separated out from the original magma—so that in some places, particularly towards the margin of a mass, the rock is often more basic than towards the centre. It cannot be said, therefore, that the hypothesis of absorption is in all cases a satisfactory explanation of the phenomena. Quite recently, however, Dr Sederholm has shown that in Finland a process of fusion and assimilation has actually taken place. Certain large areas of schistose rocks—most of them of acid composition, but some markedly basic—have been melted and transformed into granite and granite-gneiss, scattered through which more or less numerous fragments of the basic rocks are conspicuous. (See *postea*, p. 222.) Other geologists have speculated on the possibility of rock-masses having been pushed up or even blown out in fragments by vapours escaping from a batholith. But this would imply that all batholiths must have had communication with the exterior, which can hardly be admitted. On the contrary, there is no reason to doubt that many extensive masses of granite never had any communication with the surface, but cooled and consolidated at abyssal depths. On the other hand, the peculiar manner in which granite and other granitoid rocks are sometimes associated with effusive rocks, leads to the well-grounded belief that such batholiths are the cores or roots of ancient volcanoes. As an example may be cited the augite granite of the Cheviot Hills, which is closely associated with a great series of lavaform rocks and tuffs. In such cases it must be admitted that some batholiths are of less deep-seated origin than others.

It must not be supposed that granite always occurs in boss-like masses. On the contrary, it frequently appears in the form of extensive sheets of very variable thickness—and it may well be doubted whether many of the plutonic masses which have been supposed to occupy more or less vertical funnel-like cavities are really of this character. So far as one can tell from what is exposed at the surface, the so-called "bosses" may simply be partially exposed sheets, some of which, however, must have a thickness of several thousand feet. A sheet-like structure is suggested by the fact that, far removed from the margin of a granite area, inliers of the same rock are not infrequently revealed in the beds of streams which have cut their way down through a great thickness of the metamorphosed rocks surrounding the central mass.

In such cases the granite may either be of the nature of a laccolith, or thick sill or sheet, following an irregular course through the rocks among which it has been intruded (Fig. 64),

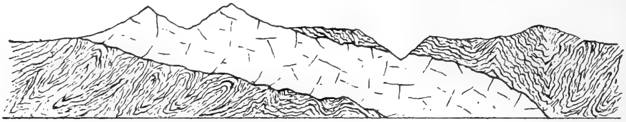


FIG. 64.

or the central mass may be a true boss from which sheets extend outwards at different levels and in different directions (Fig. 65).

The rocks for some distance around a mass of granite

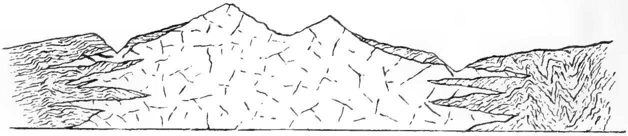


FIG. 65.

are usually more or less highly metamorphosed, and traversed by numerous dykes and veins (Plate XLIII. 2) proceeding from the eruptive rock, as will be more fully explained in the sequel.

Rocks of a more basic character than granite, such as diorite, syenite, gabbro, dolerite, etc., not infrequently occur in the form of great batholiths—usually on a smaller scale, however, than the more typical granitic masses. Like the latter, they seem sometimes to occupy the place of rocks which may either have been absorbed or pushed up and blown out. In other cases they are of the nature of gigantic laccoliths. Mr Harker has described some in the island of Skye which attain a thickness of 3000 feet. Not a few basic batholiths are apparently of less deep-seated origin than granite, and although many may never have communicated with the surface, yet there are good grounds for believing that some of them, at least, are the roots or cores of old volcanoes, the effusive products of which are grouped immediately around them. As examples of the kind, we may cite the bosses of diabase, etc., which appear in the midst of the lavas and tuffs of the Sidlaw Hills, the Ochil Hills, and other similar ranges in Central Scotland. From batholiths of all kinds proceed more or less numerous apophyses—sheets or sills, dykes, and veins—which penetrate the contiguous rocks often for considerable distances.

2. LACCOLITHS AND SILLS

The name **Laccolith** has been given to certain remarkable masses of intrusive rock, which have been described by Mr G. K. Gilbert as occurring in the Henry Mountains of Southern Utah. The same type of structure has since been recognised in the Elk Mountains, and elsewhere in North America. As these laccoliths are of late Tertiary age, many of them are still in an excellent state of preservation, and the phenomena they present enable us to understand more readily the conditions under which certain of our own intrusive rock-masses may have come into existence. The general structure of a laccolith is illustrated in the accompanying diagram (see Fig. 66). It will be observed that the intrusive rock is lenticular in shape, that it sends out sheets, dykes, and veins into the contiguous strata, and is in connection with a subjacent pipe-like feeder. According to Mr Gilbert, the molten rock has risen through this vertical pipe or fissure, but, being unable to burst across the superincumbent beds, has insinuated itself between the strata, lifted these up,

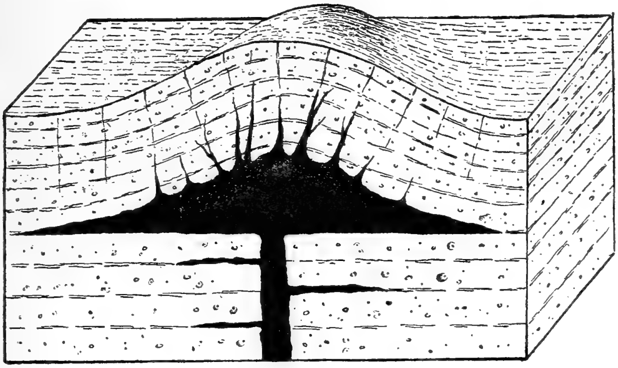


FIG. 66.—LACCOLITH.

and thus produced a dome-like elevation at the surface. Proceeding from such a laccolith are more or less numerous intrusions—some of which have been injected along the bedding-planes, while others cut across the fissured strata at all angles. While laccoliths sometimes occur singly, they more usually appear in clusters—the presence of each cluster being indicated by a dome-shaped mountain. The number of individual laccoliths in a cluster is variable—sometimes there are no more than two, in other cases there may be a score, the largest number recognised in one group being thirty.

Let us now see what light this American type of intrusive rock throws upon the phenomena of the sills or intrusive sheets which are of such common occurrence in our own country. **Sills** are eruptive masses which have usually been intruded along planes of stratification, and hence they tend to assume a more or less regularly bedded aspect. The plane along which intrusion has taken place is not necessarily, however, a plane of bedding. Some sills have followed planes of slaty cleavage and foliation, while others continue for longer or shorter distances along lines of fracture. But certainly the most typical examples are met with amongst stratified rocks, with which they have the appearance of being interbedded. Almost any kind of eruptive rock may assume the form of a sill, although the deeper-seated granitoid rocks, such as granite, syenite, diorite, etc., appear less frequently in sheet-like masses than the hypabyssal dolerites, basalts, andesites, etc. Perhaps the most typical examples of the true sill are those which occur so frequently among the Palæozoic strata of these islands—the sills of the Carboniferous areas being particularly well known. It may suffice, therefore, to give a short account of the latter.

We may note, then, that a sill, although it may seem to be interbedded as a member of one consecutive series of strata, does not exactly conform to the immediately overlying and underlying beds (Fig. 67). Followed along the outcrop, it is found now and again to leave the plane upon which it first appeared—either rising to a slightly higher or descending to a slightly lower level. Or it may suddenly break across a considerable thickness of strata and proceed thereafter along a totally different horizon. Not infrequently it contains

PLATE XLIV.

BASALT DYKE CUTTING SANDSTONE AND SHALE, KILBRIDE BENNAN, ARRAN.

Photo by H.M. Geological Survey.

[*To face page* 193.

fragments torn from the contiguous rocks; occasionally, indeed, large slabs or sheets of the invaded strata have been caught up and enclosed in the eruptive rock, and such fragments are invariably much baked and altered. Many thick sills divide into two or several subordinate sheets, each more or less closely following a plane of bedding. Often, also, dykes and veins proceed from sills into the adjacent rocks. This is frequently the case when a thick sill divides, the separate sheets being often connected by one or more dykes passing across the intervening strata. But the whole complex of sheets and dykes has obviously been intruded at one and the same time. Each independent sill or group of subordinate and associated sheets is doubtless connected with one or more vertical pipes or feeders, although these have not often been seen in section.

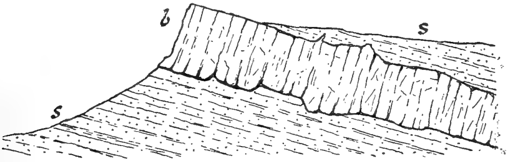


FIG. 67.—SILL OR INTRUSIVE SHEET.
b, dolerite; *s*, sandstones and shales.

The sills of our Carboniferous areas consist principally of basic rocks, mainly dolerites and basalts. Some of these are not more than a few feet or yards in thickness; others may reach and even exceed 150 feet. They are all lenticular in shape, some dying out more rapidly than others. At and near its junction with the overlying and underlying strata, a sill is almost invariably finer grained than towards the centre of the mass. Along the actual line of contact it is frequently compact and even markedly vitreous. In the case of thin sheets the texture is usually finer grained, and the rock may contain much glassy base throughout. The thicker sills, on the other hand, tend to be coarser grained and holocrystalline. Vapour cells are usually absent, although now and again sporadic areas of vesicles appear; but these are never so plentiful as to impart a scoriaceous aspect to the rock.

The strata in contact with a sill never fail to afford evidence of having been subjected to the action of heat. Both overlying and underlying strata are invariably affected, the alteration at the point of contact being often excessive. But the alteration never extends so far from the eruptive rock as in the case of granitic intrusions. Some account of these and other changes produced by sills will be considered in the sequel.

Evidence is not wanting to show that sills have now and again melted up and absorbed some of the rocks with which they have come in contact. In the Scottish coal-fields, for example, they have not infrequently eaten up thick seams of coal and black shale which they have followed as lines of least resistance. In cases of this kind the basalt-rock is usually much altered, becoming bleached white or yellow, and assuming a dull, clay-like aspect ("white trap"). Limestones are occasionally demolished in the same way, and their place taken by sills. But to what extent other kinds of rock may have been absorbed is quite uncertain. The rock of a thick sill not infrequently varies in petrographical character, being in some places less basic than the normal. But while such variations may be the result of absorption of extraneous materials, they seem just as likely to be due to magmatic differentiation, the more basic areas having separated out during the earlier stages of cooling. It may be mentioned, however, that not infrequently the intrusion of a sheet into a series of strata lying between two seams of coal or ironstone has not apparently increased the distance between those seams, as it might have been expected to do. In the neighbourhood of Dalmellington, Ayrshire, for example, thick sheets of basalt have been here and there intruded amongst a series of sandstones and shales which come between two conspicuous seams—a coal and a blackband ironstone—the distance from the one seam to the other being quite well known. In some places only one sheet is present; in other parts of the same neighbourhood there are two, while at intermediate points the pits may encounter none at all. Yet, in sinking shafts, the miners always reach the seam (ironstone) they are in search of at the estimated depth below the coal, no matter whether sills are present or not. In short, the distance between the two given horizons is neither increased nor diminished by the presence or absence of the intrusive sheets. It seems difficult to account for such phenomena (and many similar instances occur), except on the supposition that molten rock has the power of absorbing rock-material, and that, as Mr Clough has suggested, there may have been a general circulation in the mass which reduced all parts of the mixture to a uniform composition. But much petrographical and chemical research must be done before a question of this kind can be settled satisfactorily.

Sills often appear in large numbers in regions of former volcanic activity. Those associated with the Carboniferous strata of Scotland are a case in point—for volcanic action was manifested in that country again and again during Carboniferous times. It is probable, therefore, that most of the sills referred to were contemporaneous in origin with the lavas and tuffs of that period. Some of them may have been intruded before the eruptive forces had succeeded in establishing any communication with the surface; others may well be synchronous with the full development of volcanic activity; while yet others may mark the dying out of that action, when the eruptive energy was insufficient to pump lava to the surface. The out-cropping of these sills is, of course, the result of the general folding and denudation of the strata. But no one who compares the phenomena they present with those exhibited by the well-preserved laccoliths of North America, can doubt that the older and younger structures have much in common, and may well have had the same origin. Sills which crop out at the surface so as to form lofty mural escarpments have been proved in many cases to wedge out downwards, and now and again their "feeders" have been recognised. In such cases it is not hard to reconstruct the original condition of the intrusion (Fig. 68). Indeed, it may be said that most of the salient features of the American laccoliths are reproduced by the sills of our own country. The latter occur singly or in groups just as the former do. A laccolith may divide, as it were, into two or more wedge-shaped and approximately parallel sheets, and many Scottish sills behave in the same way. So again from laccoliths and sills alike veins and dykes are protruded into the contiguous strata. There is no evidence, however, that would lead us to infer that the Scottish sills affected the configuration of the surface, forming dome-shaped elevations in the same way as the laccoliths of the Henry Mountains.

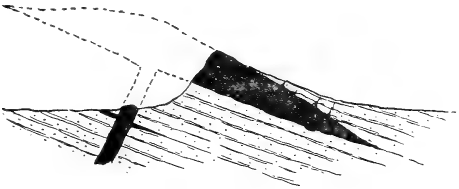


FIG. 68.—DIAGRAM OF A SILL, SHOWING ITS FORMER EXTENSION AS A LACCOLITH.

From the foregoing account of batholiths and laccoliths it is obvious that no hard-and-fast line can be drawn between the two: for many batholiths assume the laccolitic habit. Batholiths, however, usually occur on a much larger scale than laccoliths, and are, upon the whole, of more deep-seated origin, while now and again they seem to occur as bosses occupying enormous vertical pipes or funnels.

3. NECKS

Necks are pipes or conduits of eruption—the throats, in short, of old volcanoes. They are filled either with crystalline rock or fragmental materials, or with both. They are of less deep-seated origin than batholiths; indeed, portions of the old volcanic cone are still to be seen surrounding a neck in some cases. As a rule, however, the cones have been entirely demolished—only the plugged-up vents remaining. Not a few of these seem to represent very small volcanoes—the products of single eruptions, like that which, in 1538, gave birth to the tuff and cinder cone of Monte Nuovo (Bay of Baiæ). Others, again, are obviously the relics of much more important volcanoes, from which were discharged not only fragmental materials but streams of lava. Between necks of this kind and certain bosses no hard-and-fast line can be drawn. Some of the latter, as we have seen, appear to have had communication with the surface, and these, therefore, might equally well be described as necks. That term, however, ought rather to be reserved for the less important pipes or funnels of eruption—most of which, indeed, represent only the uppermost or terminal portions of such pipes. For, even in the case of the most highly denuded neck, we have no reason to suppose that the portion remaining occurred at any great depth below the base of the old volcanic cone to which it led. It is conceivable that, could we trace an important neck downwards, we should find it gradually assume the character of a more or less funnel-shaped boss, and this in its turn might, at a greater depth still, expand into a yet more extensive batholith. It would seem, therefore, as if the structure now presented by many an old focus of eruption, may have been determined by the degree of denudation which it has experienced. With a minimum amount of erosion we have the cone of the extinct volcano, still recognisable as such. Increased erosion removes the cone, and then only a neck remains; until after some prolonged period the whole region becomes so reduced that the batholith or more deeply-seated portion is laid bare.

Seen in groundplan, typical necks tend to be more or less circular or elliptical in form, but they are frequently irregular. Occasionally, however, such irregular shapes are suggestive of two or more closely adjacent necks having coalesced. Not infrequently, fissures, filled with agglomerate or tuff, pass outwards from a neck into the adjacent rocks. More remarkable than these, however, are certain vertical fissures of eruption which occur independently, or seem, at least, to have no connection with necks or pipes. At the surface, these appear in groundplan as long, lenticular ribbons or belts, or they may expand and contract irregularly. They are filled with fragmental materials, and thus might be tersely described as *agglomerate-dykes*. Fissures of eruption of this kind are not common, and seem to be confined to regions where volcanic rocks are well developed. Isolated examples occur in the Sidlaw Hills and in South Ayrshire, and they are met with likewise in the Cheviot Hills. Necks often appear upon a line of fault or dislocation, but in many cases no such connection can be traced. Although they now and again occur singly, they more usually cluster in groups within a limited area. They vary much in size—some measuring only a few yards across, while others may be several hundred yards in diameter; exceptionally, they may reach or even exceed a mile in width. They usually form more or less abrupt knolls or isolated hills, which vary in shape according to the nature of the materials of which they are composed. Many are more or less conical; others are somewhat steep and not infrequently craggy; while yet others are smooth and rounded. The rock occupying a neck may be crystalline, as basalt, andesite, phonolite, quartz-porphyry, felsite, etc. (see Fig. 69); or it may consist of fragmental materials, as agglomerate or tuff (see Fig. 70), or both fragmental and massive crystalline igneous rocks may be present (see Fig. 71). Frequently the

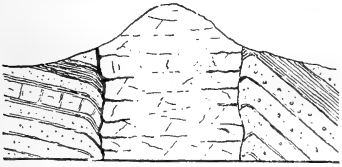


FIG. 69.—NECK OCCUPIED BY CRYSTALLINE IGNEOUS ROCK.

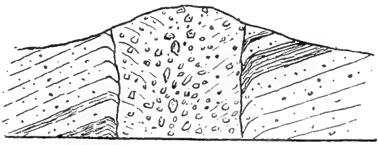


FIG. 70.—NECK OCCUPIED BY AGGLOMERATE.

fragmental materials are extremely coarse—an aggregate of angular and subangular blocks and smaller stones in a matrix of finely comminuted débris, which may be meagre or relatively abundant. All the fragments may consist of crystalline igneous rock of one or more kinds, or these may be commingled with the débris of sedimentary rocks—the relative proportion of igneous and sedimentary materials varying indefinitely. Sometimes the contents of a neck consist of derivative rocks only, as sandstone, shale, limestone, ironstone, coal, etc. In necks composed mostly or exclusively of igneous materials, large broken crystals of various volcanic minerals sometimes occur, as hornblende, augite, biotite, sanidine, pyrope, etc. Still more remarkable is the appearance in some tuff-necks of abundant small and larger fragments of coniferous wood. Although the fragmental materials are usually somewhat coarse, yet not infrequently these are associated in the same neck with areas of much finer grained tuff; while in some cases the whole neck consists of fine tuff, which now and again has been so altered as to assume a crystalline or subcrystalline aspect.

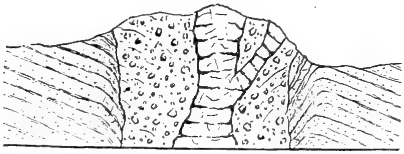


FIG. 71.—NECK OCCUPIED BY AGGLOMERATE AND CRYSTALLINE IGNEOUS ROCK.

The agglomerate and tuff often exhibit more or less distinct traces of a centroclinal dip—the materials being rudely bedded around the marginal area and inclined inwards towards the centre, where all trace of bedding is usually lost, although occasionally the coarse material appears roughly arranged in nearly vertical lines. Not infrequently it is about the centre of a neck that the larger blocks and stones are most abundant; but in many necks no such aggregation can be traced.

Massive dykes and branching veins of basalt or other crystalline igneous rock often pierce and ramify through the agglomerate and tuff. These may be confined to the neck itself, or pass outwards into the contiguous strata. The massive rock which often completely fills a neck is usually traversed by well-marked horizontal jointing, but in the case of large necks these joints are often confined to the marginal area, the rock towards the centre being, as a rule, very irregularly jointed.

The strata in immediate contact with a neck are often bent over suddenly, so as to dip abruptly against the old pipe of eruption—not infrequently, indeed, they are quite vertical, and sometimes much jumbled and broken, large blocks, slabs, and reefs having been detached or partially detached from the walls of the neck, so as to become enclosed wholly or partially in the tuff and agglomerate, while irregular veins of tuff pass outwards into the contiguous strata as if filling rents and fissures. Now and again, so great is the confusion that it is hard to follow the actual junction between the neck and the contiguous rocks. In such cases it seems as if the wall of the old funnel had collapsed and fallen in. The effect of heat upon the rocks abutting upon a neck are sometimes very notable—sandstones for a few yards away being converted into quartzite, and shales baked into a kind of porcellanite. On the other hand, not infrequently no alteration of any kind can be seen, coal having sometimes been mined close up against a neck without showing any trace of having been subjected to the action of heat. In other cases, coal has been rendered quite useless for many yards away from a neck, changed in fact into a soft, sooty substance. The amount of alteration produced bears no relation to the size of a neck; for while much change may occur round a small one, little or no alteration may be visible round one of much larger dimensions.

Explanation of Phenomena.—The necks described above obviously indicate the sites of former volcanoes. Many occur along lines of dislocation, just as is apparently the case with not a few volcanoes at the present time. On the other hand, a large number of necks seem to have no connection with any lines of weakness, and such pipes of eruption, therefore, must have been blown or blasted out by escaping vapours. Many necks probably indicate small puys—products of a single eruption, from which only loose ejecta were emitted. From others, one or more flows of lava have taken place. When the tuff and agglomerate of a neck consist wholly or largely of igneous materials, it is obvious that molten matter must have risen in the throat of the old puy, although it may never have flowed out as a lava. It is quite possible, however, or even probable, that lava-streams may have proceeded from many necks, around which no remains of such flows now exist. Subsequent denudation would well account for their disappearance, for not only have the volcanic cones been removed, but the surface upon which these were built up has also often been carried away. In the case of those necks which contain no igneous materials, but are filled exclusively with the débris of derivative rocks, it is clear that if at the time of eruption molten matter was present at all, it could only have been at a relatively great depth. The character of the débris, at all events, shows that only explosive vapours escaped by such pipes and funnels. While there is reason to believe that some necks may represent subaërial volcanoes, not a few are certainly of subaqueous origin. In the former case no trace of the old cones or the surface upon which they were accumulated has been preserved, the pipes alone remain to tell their tale. From the fact, however, that these sometimes contain quantities of coniferous wood, which from its appearance must have been buried in a fresh state, it has been inferred that some volcanoes were probably subaërial, and that after their extinction they became clothed with a coniferous vegetation. The majority of the necks met with in Scotland, however, would seem to represent subaqueous volcanoes. This is suggested by the simple fact that the cones are occasionally preserved—which could hardly have happened had the volcanoes erupted upon a land-surface. The volcanoes referred to obviously discharged their ejecta upon the gradually subsiding bed of sea, lagoon, or lake, and thus the sheets of materials that accumulated round the vents passed outwards in all directions and became interstratified with sediments, charged with the organic remains of the period. When at last the volcanoes became extinct, they were finally covered up by successive deposits of sediment, and thus the cones escaped the denudation that ere long must have demolished them had they been formed upon dry land (see Fig. 72).

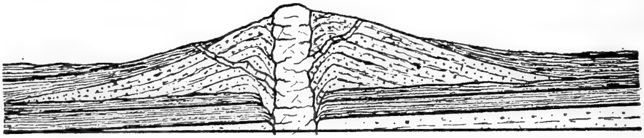
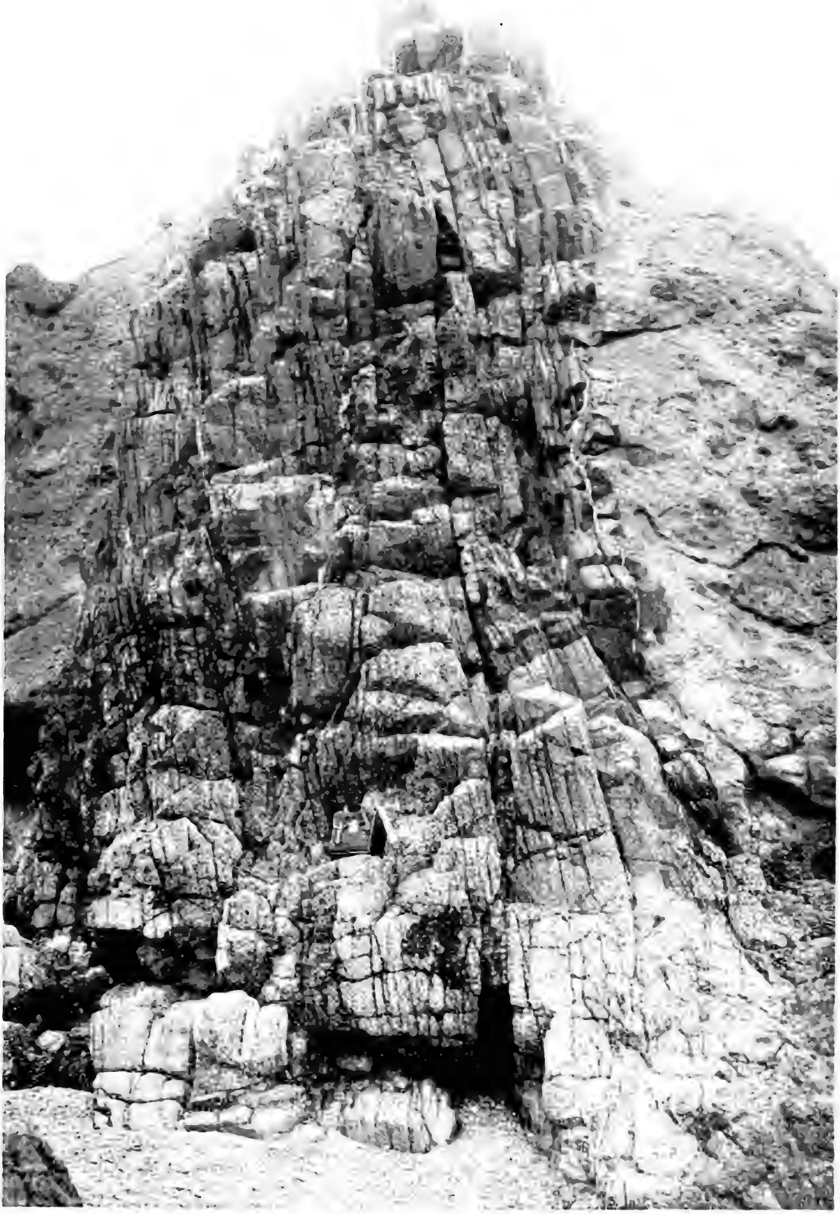


FIG. 72.—CONE OF AGGLOMERATE, AND NECK OF CRYSTALLINE IGNEOUS ROCK.

The inward dip of the strata surrounding a neck has been attributed to that sinking of surface which so frequently takes place near a volcanic centre. After prolonged activity the rocks surrounding a vent probably become undermined, and this must tend to bring about subsidence in its immediate neighbourhood. In the case of extensive necks, from which much material has been discharged, the inward dip of the surrounding strata may be due to some such cause. A large number of the necks, however, are too small and erupted for too short a period to have produced any marked subsidence of the surrounding rock-masses—and yet the abrupt inward dip of the strata surrounding such necks is quite as

DYKE, 2 FT. BROAD, CUTTING SANDSTONE, PORT LEACACH, ARRAN.

Photo by H.M. Geological Survey



THE "YELLOW MAN." DYKE CUTTING VOLCANIC AGGLOMERATE, SHORE NEAR NORTH BERWICK, HADDINGTONSHIRE.

Photo by H.M. Geological Survey.

[*Between pages* 200 *and* 201.

conspicuous as in the case of larger ones. It would seem more likely that the sudden inward dip of the rocks abutting upon a neck is due partly to the downward drag of the fragmental materials while they were slowly subsiding and becoming consolidated, and partly, perhaps, to the unequal yielding of the strata themselves before the pipes were filled. When a subaërial puy became extinct, the loose materials forming the cone would naturally tend to slip down into the crater and funnel, while at the same time the walls of the vent, exposed to the action of springs and to weathering generally, would also supply material—all this débris falling into the vent would form a steep, rudely-bedded talus having a centroclinal dip. The falling away of the softer and less resistant rocks in the walls of the vent would tend to undermine the less yielding beds above them, and thus cause these to bend over. Finally, when the pipe had become filled, the consolidating débris, as it subsided, would drag down the rocks forming the walls, and thus increase their inward dip. In the case of a submarine puy there would be no weathering action upon the walls of the pipe, but it seems at least unlikely that the rocks should remain unaffected, and that larger and smaller portions should not become detached, and thus cause undermining and bending downwards of the rocks above. It is worthy of note, however, that this inward dip of the strata abutting against a neck does not invariably occur.

Necks, like batholiths, may belong to almost any geological period. But inasmuch as a typical neck represents the upper portion of a pipe of eruption, and consequently is not of deep-seated origin, only those of subaqueous eruptions can date back to the earlier geological ages. Now and again, it is true, some Palæozoic necks seem to have erupted on land, but, if so, they must ere long have been submerged, for only in this way could these have escaped demolition. Exposed for a prolonged period to denudation, not only must the cones have been demolished, but the ancient land-surface on which these stood must have been so lowered that the upper portions of the pipes of eruption—the necks—would have been planed away, and the deeper seated roots of the old volcanoes laid bare.

CHAPTER XIV

ERUPTIVE ROCKS: MODE OF THEIR OCCURRENCE—*continued*

Dykes and Eruptive Veins—their General Phenomena. Composite Dykes. Exogenous or Intrusive Veins—their association with Batholiths, etc. Endogenous or Autogenous Veins. Pegmatite Veins; General Phenomena of Contemporaneous Veins. Segregation Veins. Effusive Eruptive Rocks—Crystalline Effusive Rocks and Pyroclastic or Fragmental Effusive Rocks.

4. DYKES AND ERUPTIVE VEINS

ERUPTED matter which has solidified in a more or less steeply inclined or vertical and somewhat even-sided fissure, is called a **dyke,** while the term **eruptive vein** is usually reserved for the more irregular and frequently tortuous and branching intrusions. But this usage is not invariable—many geologists employing the terms interchangeably, while others designate as "dykes" all the larger intrusions, whether wall-like or tortuous, and restrict the term "vein" to the smaller injections.

Eruptive veins and dykes may consist of almost any kind of igneous rock. Frequently they proceed visibly from large masses of eruptive rock—bosses or sheets, as the case may be. At other times no such relationship can be observed, although we can hardly doubt that if dykes and veins could be followed downwards they would be found to proceed in the same way from larger masses of intrusive character.

Wall-like intrusions are of common occurrence in this country—the most notable examples being the remarkable basalt-dykes which are so abundantly developed in Central and Western Scotland (see Plate XLVIII.). Sometimes these dykes give rise to conspicuous surface-features—forming, as the case may be, either prominent ridges or elongated depressions, according as the basalt or the rock it traverses has offered the stouter resistance to denudation. When the former is the case, a dyke may rise wall-like above the general level of the country, continuing its course uninterruptedly for a longer or shorter distance across hill and dale. When, on the other hand, the rocks it cuts are more resistant than itself, a dyke indicates its presence by a long narrow trench or depression instead of a prominent ridge. The course followed by a dyke is, as a rule, remarkably straight or direct, though often gently sinuous. Occasionally, however, this regularity may be interrupted by one or more zig-zags or sharp bends. It is noteworthy that dykes which traverse sandstones and shales are usually straighter or more regular than those which cut through greywackés, crystalline igneous rocks, and schists. While some dykes have come up along lines of dislocation or true faults—the great majority occupy fissures or rents along which no displacement has occurred (Plates XLIV., XLV.).

Dykes vary in extent—some being considerably less than a mile in length, while others have been followed for distances of 50 or even 70 miles and more—often preserving throughout their course a wonderfully uniform thickness. Some of the smaller dykes do not seem to be more than a few inches in thickness—the longer ones, however, are much thicker, and sometimes reach, or even exceed, 100 feet in width. But although the shorter dykes usually tend to be thin, and the longer ones to be thick, there is really no definite proportion between the extent and the width of dykes in general. A dyke 20 feet thick may have a longer range than one double its width—or the converse may be the case. Although no general average can be given for the thickness of the more persistent dykes, yet it may be said that dykes measuring 20 to 40 feet across are among the commonest of those which have been followed for any considerable distance.

Occasionally, a dyke divides into two or more smaller ones—each pursuing the same general direction. Now and again, also, eruptive veins and veinlets proceed from a dyke, but this is apparently exceptional. Dykes often wedge out suddenly, both in lateral and vertical directions. Traced across country, they not infrequently seem to die out, and then after a shorter or longer interval they may as suddenly reappear. When a dyke of this kind is represented upon a map, therefore, we have the appearance of two or more dykes following each other along the same line. That the apparently separate dykes, however, are really portions of one and the same intrusion, has now and again been demonstrated in the coal-bearing districts—where a dyke has been followed continuously throughout all the coal-workings, although it fails in some places to reach the surface. Sometimes, indeed, a dyke cuts the lower coals but does not penetrate the higher seams in one and the same coal-pit.

Basalt-dykes are jointed most prominently at right angles to their direction—the jointing being frequently prismatic (see Figs. 73, 74). But, in some cases, the joints run parallel to the walls, so as to give the rock a kind of flaggy structure (see Plate XLVI.). Parallel jointing of this nature is usually, however, confined to the marginal areas of the rock.

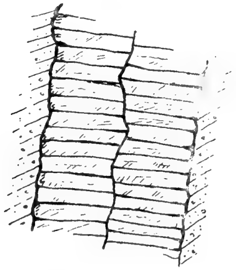


FIG. 73.—PRISMATIC JOINTING IN A DYKE.

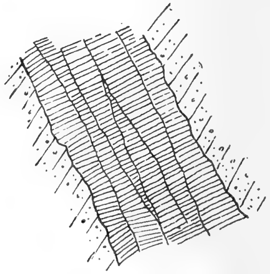


FIG. 74.—COMPLEX PRISMATIC JOINTING IN A DYKE.

The rock of a dyke is almost invariably finer grained along its margins than towards the centre—a structure which is most conspicuous in the case of the thicker dykes. Thin dykes are usually fine-grained throughout, yet even these tend to be most compact towards the sides. This structure is obviously due to the chilling effect of the contiguous rocks—the dyke along the line of junction becoming more or less markedly vitreous. Small vapour pores often appear at or near the margin, while larger pores, vacuoles, and occasionally irregular shaped cavities of some size occur towards the centre, either sporadically or forming a continuous medial zone running parallel to the direction of the dyke (Fig. 75).

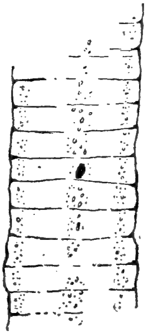


FIG. 75.—DYKE, SHOWING USUAL POSITION OF VAPOUR PORES AND VESICLES.

Dykes affect the contiguous rocks much in the same way as sheets, but to a less extent. In the case of dykes only a few feet in thickness, the alteration produced is very slight, but the broader dykes may bake and indurate the rocks for a yard or two away.

Occasionally a dyke is the product of more than one intrusion—the same fissure having been rent open again and again so as to allow of successive injections of the same kind of molten matter—the younger injections being often readily recognised by the "chilled edges" which they present to the rock they traverse. In other cases, however, the earlier and the later injections may be distinctly different—an eruption of basic rock having either preceded or succeeded one of acid rock. In such composite dykes a clear line of demarcation separates one injection from another. But in certain broad dykes of a composite structure, no such lines of separation are visible—one kind of rock gradually merging into another, so that the whole complex must obviously have been injected at or about the same time. The rock forming the sides of a dyke of this character is usually more basic than the central and larger portion. Near Liebenstein, in the Thuringian Forest, for example, there is a broad dyke, the flanks of which consist externally of melaphyre, which graduates inwards into syenite-porphyry, as this in turn merges into granite-porphyry, of which the central and major mass of the dyke is composed (see Fig. 76). Dykes of a like kind have been described by Professor A. C. Lawson as occurring in the Rainy Lake region of Canada—where in one and the same dyke the andesite of the marginal areas shades off inwards into a central quartz-gabbro. Phenomena of this kind are doubtless due to magmatic differentiation.

Eruptive veins and dykes, as already indicated, often follow somewhat erratic courses. The more or less regular basalt-dykes of Central Scotland have been cited as good examples of wall-like intrusions. It need hardly be said, however, that injections of basalt, as of any other kind of igneous rock, are often extremely tortuous and branching (see Plate XLVI.). The veins usually associated with granite, however, may be taken as somewhat characteristic of their kind. Of these veins two types are recognised—*exogenous* or *intrusive* and *autogenous* or *endogenous* veins.

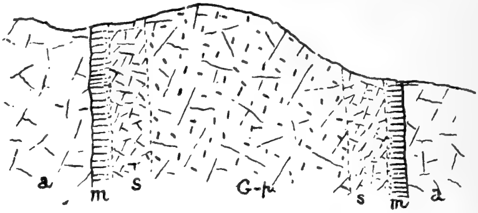


FIG. 76.—COMPOSITE DYKE, LIEBENSTEIN (THURINGIA). (After Dr K. Keilhack).
a, *a*, granite; *m*, *m*, melaphyre; *s*, *s*, syenite-porphyry; *G-p*, granite-porphyry.

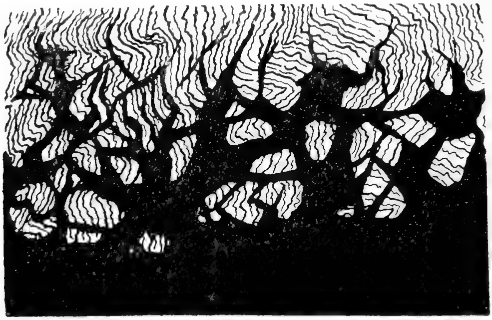


FIG. 77.—VEINS PROCEEDING FROM A MASS OF GRANITE.

Exogenous or Intrusive Veins.—These are simply protrusions proceeding from a mass of granite into the contiguous rocks. They vary in thickness from mere lines or threads up to many feet or yards. Usually very tortuous, they ramify in all directions, intercrossing, dividing and subdividing again and again. Now and again, extremely thin veins have forced their way along planes of cleavage or of foliation. As a rule, however, small and large veins alike follow no definite direction—save that they stream outwards from the margin of the parent batholith—gradually diminishing in numbers as they proceed. In many cases the veins form a perfect network amongst which irregular fragments and larger masses of the invaded rocks appear as if entangled—forming what is termed an *injection plexus*. All the phenomena, indeed, seem to suggest that before the veins were injected the rocks surrounding a batholith had been so profoundly shattered, that molten matter found little difficulty in making its way amongst the fractured and sundered masses (Fig. 77).*

The rock of these veins, especially the smaller ones, is usually finer grained than the granite-mass from which it comes. It is notable, also, that not infrequently it differs in petrographical character from that of the parent-rock—many of the veins consisting of quartz-porphyry or felsite.

Endogenous or Autogenous Veins.—Some of these are composed of finer grained rock than the granite, and usually differ from it in being more acid. Others, again, are characterised by the intergrowth of the constituent quartz and felspar. These are the *pegmatite-veins*. They are generally coarser grained than the rock they traverse. The precise mode of origin of these endogenous veins is quite uncertain. Although obviously younger than the rock they cut, they yet appear to form portions of the same intrusive mass—to be merely modifications, as it were, of the granite itself. Hence they are often spoken of as **contemporaneous veins.** They are supposed to belong to the period of cooling and consolidation, and to have been injected from still liquid portions of the magma into rents formed during movements of the surrounding solidified or partially solidified mass. This seems a plausible explanation of the fine-grained autogenous veins, but it does not account for the structure of the coarsely crystalline pegmatite veins.† The contemporaneous origin of both fine-grained and

---

* The exploitation of "contact ore-formations" (see Chapter XVII.) has shown that the ore-bearing rocks overlying and surrounding a plutonic mass are often much jumbled and shattered—shales and limestones, for example, being converted into breccias which are usually highly silicified. These brecciated masses may occur at a considerable distance from the intrusive rock, and possibly owe their origin to the explosive action of steam and vapours. Not infrequently they are traversed by dykes and eruptive veins, but these could not have caused the shattering of the rocks, for the same dykes cut through undisturbed areas where no brecciation is visible.

† According to Professor Arrhenius, a granite magma containing sufficient water would, in cooling, probably separate into two portions—the product of the separation appearing as an aqueous solution in which would be concentrated such bodies as are more soluble in water than in the silicate magma. Owing to their greater mobility than the magma, these aqueous

coarse-grained autogenous veins is shown by the fact that they are not always sharply separated from the rock on either side, as is the case with exogenous or intrusive veins. On the contrary, the mineral constituents of an autogenous vein often interosculate, as it were, with those of the surrounding granite—the crystals of the latter being so interlocked with those of the vein, that the two rocks are not readily separated along their line of junction.

Contemporaneous veins are met with in many other eruptive rocks, more particularly in batholiths and thick sills of such rocks as gabbro, dolerite, and diorite.

Yet another kind of autogenous veins may be mentioned. These are the so-called **segregation veins.** They are distinguished from the other varieties described by the fact that they merge gradually into the enclosing rock of which, therefore, they are merely a coarsely-crystalline modification. They have not been injected into rents or fissures after the manner of other endogenous veins, but their precise mode of origin is obscure. They appear to be the result of some process of segregation, and to represent zones or lines along which crystallisation of the constituent minerals was more readily developed than elsewhere in the same rock-mass. Although of common occurrence in eruptive rocks, segregation-veins are not confined to these, but make their appearance also in certain schists, and even in derivative rocks which have been more or less metamorphosed.

EFFUSIVE ERUPTIVE ROCKS

Effusive rocks have been erupted at the earth's surface, and are of two types, *crystalline* and *fragmental*—that is to say, *lavas* and *tuffs*. As they frequently occur interstratified in a conformable manner with derivative rocks of all kinds, they are often termed *contemporaneous* or *interbedded.*

(*a*) **Crystalline Effusive Rocks.**—The general petrographical characters of these rocks have been already set forth. It will be remembered that lavas are often scoriaceous above and below, and in some cases may be more or less porous and cavernous throughout. The vapour-cavities are often flattened or drawn-out in the direction of flow. In all such lava-form rocks residual glassy matter is very commonly present, especially towards the upper and under surfaces.

---

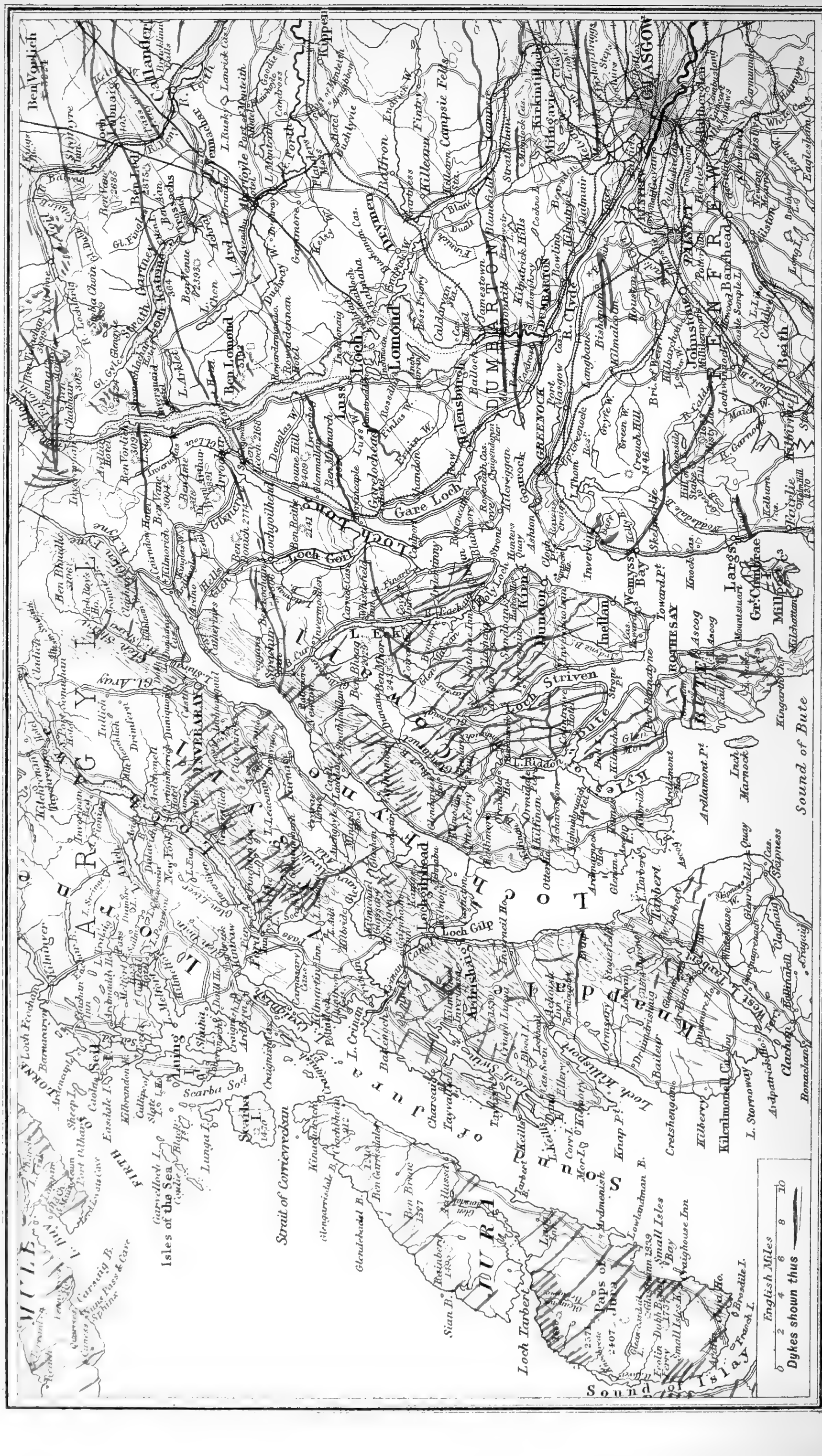
solutions might send out the very finest threads and veins into the contiguous rocks, while other portions would collect as geodes and veins in the interior of the magmatic mass. As the solution cooled, one substance after another would separate out—and if the cooling process were not too rapid, the minerals would segregate in large crystals, such as characterise the pegmatite-veins.

VEINS OF BASALT INVADING SANDSTONE, SHORE NEAR KINGSCROSS POINT, ARRAN.

Photo by H.M. Geological Survey.

[To face page 208.

THE DYKES OF CENTRAL SCOTLAND



[*To face page* 209.

The mineral constituents also frequently show glass- and stone-inclusions, while liquid-cavities are relatively seldom seen. Now and again the lower part of a lava is crowded with indurated arenaceous and argillaceous matter, and contains occasionally well water-worn stones, as if the molten matter had flowed over the bed of the sea or of a lake or river, and thus caught up and enclosed some of the sedimentary materials lying in its path. Even fragments of trees have been found included in the basal portion of a lava—as in the case of a Carboniferous basalt-flow near Kinghorn, Fife. In all these respects effusive crystalline rocks differ markedly from intrusive rocks. As further differentiating lava-form rocks from sills, with which they might sometimes be confounded, it may be noted that while the former may produce some induration of the rocks on which they rest, they never affect the overlying strata. Obviously, the superjacent beds have been deposited over the surface of the lava-form rock after consolidation had taken place, for the lines of bedding follow all the irregularities of the underlying rock-surface. When this is much rent and cleft, the cavities have been gradually filled up with sediment, while now and again fragments of the scoriaceous crust of the old lava have been detached and enclosed in the immediately superjacent aqueous rock. Again, it may be noted that lava-form rocks are usually associated with stratified tuffs (see Fig. 78).

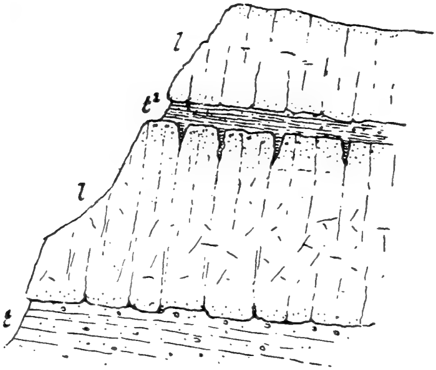


FIG. 78.—EFFUSIVE IGNEOUS ROCKS.
l, *l*, lava-flows; *t*, tuffaceous sandstones; t^1, tuffaceous shales.

Flows vary in thickness, some being only a few feet, while others attain a depth of many yards. The more basic lavas generally preserve a somewhat equable thickness, the intermediate and acid kinds tending rather to be irregular, so that they thicken and thin-out more or less rapidly.

(*b*) **Pyroclastic or Fragmental Effusive Rocks.**—The tuffs usually associated with lava-form rocks vary in character. As might have been expected, their dominant ingredients consist of the comminuted débris and larger fragments of the lavas they accompany. Thus we have basalt-tuff, andesite-tuff, trachyte-tuff, etc. All varieties of texture and structure are met with, some rocks being very fine grained, while others are mere aggregates of lapilli and blocks—finer and coarser grained materials often rapidly alternating in a vertical section. Bedding is usually pronounced—many of the finer tuffs being beautifully laminated. Occasionally, very large sporadic blocks may be encountered in a bedded mass of small lapilli, and generally increase in numbers as the old focus of eruption is approached. Tuffs are frequently interstratified with ordinary sedimentary beds, and when such is the case the tuffs themselves usually contain a larger or smaller proportion of arenaceous or argillaceous materials, and thus frequently graduate into sandstone and shale. Fossils may be included not only in the sedimentary beds associated with tuffs, but in the tuffs themselves. Fragments of plants, and various marine organic remains, for example, not infrequently occur in the tuffs and tuffaceous sandstones and shales, which are associated with the andesitic lavas of the Carboniferous system in Scotland.

Mode of Occurrence of Effusive Rocks.—Sometimes a flow, with its accompanying tuff, occurs singly; more usually, however, flows and tuffs appear in consecutive series. Some effusive rocks, occupying a limited area, are obviously the products of an isolated volcano. Others extend over very wide regions, and appear to represent the products of a series of more or less closely associated foci of eruption, the successive lavas and tuffs discharged from the several vents interosculating and overlapping. A good example is furnished by the eruptive rocks of the Sidlaw and Ochil Hills, some of the old vents from which these were discharged being still recognisable in the great necks and bosses which have been exposed by denudation. In other cases of widely extended effusive rocks, we appear to have the products of vast fissure-eruptions. Of such a character are the plateau-basalts of the Western Islands of Scotland, Antrim, the Færöe Islands, Iceland, etc. At the time of these eruptions, the whole wide region extending from the British Islands to Greenland appears to have been underlaid by a vast sea of molten matter, which rose to the surface along rents in the crust and deluged the surrounding areas with floods of lava. Such rents and fissures were doubtless the result of earthquake action; and many of them did not reach the surface, dying-out upwards at various levels. Into these, however, molten matter found its way, forming the great series of basalt-dykes shown in the map, Plate XLVIII.*

Sandstone Dykes.—Here brief reference may be made to certain abnormal dykes, occurring in California and elsewhere in North America. They are composed of sedimentary materials, and occupy vertical fissures, which have been filled not from above but from below. Some of these dykes have a length of several miles, and their precise mode of origin is obscure. The sand may have been introduced from below during earthquake movements. For unconsolidated materials, such as water-logged clay and sand, when buried under a considerable thickness of superincumbent rock, are ready to rise towards the surface along any open fissures that may be formed. Occasionally boring operations in our coalfields have been impeded in this way by the more or less rapid rising in a bore-hole of soft clay, coming from a considerable depth.

---

* It ought to be mentioned, however, that some of the dykes shown upon the map date back to much earlier periods. For example, certain dykes traversing the Carboniferous tracts appear to be of late Carboniferous age.

CHAPTER XV

ALTERATION AND METAMORPHISM

Rock-changes induced by Epigene Action. Deep-seated Alteration or Metamorphism. Degrees of Metamorphism. Thermal or Contact Metamorphism. Regional Metamorphism — Plutonic, Hydrochemical, and Dynamo-metamorphism.

Alteration by Epigene Action.—Very few rocks have not undergone some change since the time of their formation. At and for some distance down from the surface water passes more or less readily along the various planes of division by which all rocks are traversed—not only so, but it soaks into the rocks themselves, occupying their minutest pores and capillaries. In this way chemical changes of greater or less importance are effected, by which certain rocks tend to become disintegrated, while others, on the contrary, are more firmly consolidated. Crystalline igneous rocks, as a rule, are prone to decay—their felspathic and ferromagnesian constituents being readily broken up chemically, and some portion of their substance removed in solution. Many schistose rocks experience the same kind of change—a change which usually results in weakening a rock—its hardness and solidity becoming more or less impaired. Sedimentary rocks, on the other hand, being themselves the products of decay and disintegration, and consisting therefore of more stable ingredients, are less liable to those chemical changes to which igneous and schistose rocks alike are subject. Instead of being weakened by the action of percolating water, they are often strengthened by the introduction into their pores and capillaries of various mineral substances which bind their ingredients more firmly together. To this general rule there are, as might have been expected, many exceptions. Percolating water, which introduces cementing materials, may in the course of time redissolve these and carry them away. Again, rocks of chemical origin, such as travertine, dolomite, etc., and rocks organically derived, such as chalk and many limestones, being all more or less soluble, are readily attacked by percolating water. To sum up in a few words, it may be said that the chief chemical changes induced in rocks by the process of weathering, consist of solution, oxydation, hydration, and the formation of carbonates and sulphates.

Metamorphism.—The changes brought about by epigene action, however extreme they may be, must not be confounded with true metamorphism. The term "metamorphic" is applied properly to rocks, the texture, structure, and mineralogical constitution of which have been more or less profoundly affected. Metamorphism, however, varies much in its intensity. It may be so inconsiderable as not to obscure all original characters, or so extreme that we can only conjecture what the nature of the unaltered rock may have been. True metamorphism, especially that which has resulted in crystallisation and recrystallisation and the production of foliation, would seem to have taken place at some depth from the surface, and to have been induced proximately by heat, usually if not always in the presence of water or vapours. Metamorphic rocks have a certain aspect which commonly serves to distinguish them from rocks altered by epigene action alone. The great majority are more or less indurated, crystalline, or subcrystalline, and foliated or schistose. Seldom, indeed, can an igneous or derivative rock altered by epigene action be mistaken for a metamorphic rock. Nevertheless, there are certain altered rocks which in hand-specimens might quite well pass for products of metamorphism. Sands and sandstones, for example, have frequently been transformed into quartzite by percolating water carrying silica in solution; and hand-specimens of such rocks might readily be taken for quartzites of truly metamorphic origin. Serpentine affords another example of a rock which has resulted sometimes from epigene and sometimes from hypogene action. Metamorphic serpentine, however, is usually foliated, and, moreover, is always associated with other crystalline schistose rocks. On the other hand, serpentine of epigene origin is not foliated, and is found traversing rocks of all kinds, while its igneous character can readily be determined by field observation. Cases like these, however, are exceptional, and there is usually no difficulty in distinguishing in the field between metamorphic rocks and rocks which have been altered by epigene action.

There are many degrees of metamorphism. In some cases, rocks have been so slightly changed that their distinctive characters have remained unaffected. Reference has already been made to the transformation of a relatively soft quartzose sandstone into a hard quartzite. Here the only conspicuous change is one of texture: while becoming indurated, the original rock has retained its chemical composition and structure. Planes of stratification, diagonal or cross-bedding, ripple-marks, etc., may be as conspicuous in a quartzite as in any unaltered sandstone. In most cases, however, a rock, while it retains its chemical composition unchanged after metamorphism, has yet been profoundly modified as regards its constitution and structure. An argillaceous shale, for example, may be transformed into an andalusite-mica-schist, without either loss or gain of mineral substance. Similarly, eruptive rocks, such as granite, gabbro, diorite, etc., may be rendered schistose—the ultimate chemical composition of each remaining practically unchanged. Nor is foliation the only modification induced in eruptive masses—for one or other of their essential constituents may be transformed—pyroxene, for example, has often been changed into amphibole. Thus, dolerite has not infrequently been transformed into hornblende-schist. Although the chemical composition of rocks has not usually been much affected by metamorphism, yet this is not invariably the case. Occasionally, there has been a loss of mineral substance—volatile elements, such as carbon-dioxide and water, having been driven out—more frequently, however, the opposite has been the case, and new materials (silica, alkalies, fluorine, etc.) have been introduced.

Two phases of metamorphism are recognised, namely, (*a*) thermal or contact metamorphism, and (*b*) regional or general metamorphism.

(*a*) **Thermal or Contact Metamorphism.**—Reference has already been made to the fact that rocks which have been overflowed or invaded by molten matter are usually more or less altered along the line of contact. The changes effected by a lava-stream are not particularly conspicuous, and consist chiefly of induration, often accompanied in the case of clay by a change of colour and the production of prismatic jointing. The changes caused by intrusive eruptive rocks, however, are usually more pronounced. Sometimes, indeed, they are of slight importance and confined to the immediate proximity of the intrusion; but at other times they may extend outwards from the margin of the eruptive mass for hundreds or thousands of yards. The extent and intensity of the metamorphism depend partly upon the character and mass or volume of the intruded rock, and partly upon the nature of the rocks invaded. Other things being equal, more change is effected by an extensive eruptive mass than by a smaller intrusion of the same kind of rock, while certain rocks, owing to their composition, are more readily influenced than others.

Some reference has already been made to the kind of changes produced upon contiguous strata by basic intrusive rocks—such as the conversion of coal into coke, anthracite, or graphite, the crystallisation of limestone, the induration of rocks generally, the production of prismatic jointing, etc. These and other changes are often exhibited by the larger and smaller fragments of sandstone, shale, etc., which have been torn from their parent strata and enclosed in an eruptive rock. The larger included slabs and blocks are usually much shattered, baked, corroded or fused superficially, and even occasionally rendered vesicular or scoriaceous. Pieces of felspathic sandstone have been thoroughly fused, while fragments of dark shale have been burnt red and baked into a hard porcellanite. Similarly, when basalt has caught up and enclosed portions of some igneous or schistose rock, such as granite or gneiss, these have been either partially or completely fused to a dark green or black glass. It is noteworthy that, in the fused portions of such included blocks and fragments of various kinds of rock, new minerals (cordierite, spinel, sillimanite, pyroxene, etc.) have not infrequently been developed.

Similar changes are effected on the rocks *in situ* along their line of contact with sills and dykes of basalt or other basic igneous rock. Fusion, however, is confined to the actual line of contact, while induration and other changes may extend outwards for many feet or yards, the width of the metamorphosed belt being dependent on the volume of the eruptive mass, and to a large degree also upon the character of the surrounding rocks. Thus coals may become coked at a distance of many yards from a basalt, while the intervening sandstones and shales may show little or no change beyond slight induration or discoloration. Limestone is likewise somewhat readily influenced by basalt—the rock becoming converted into a crystalline marble, for a few feet or more from the line of contact.

But the most notable contact metamorphism is induced by great plutonic batholiths—more especially by granite. The phenomena are perhaps most conspicuously displayed in places where the rocks surrounding a granite consist of what were originally more or less unaltered greywacké and shale, or other strata of derivative origin. In such a region one can study all the various modifications which the strata undergo, as they are followed towards their contact with the eruptive mass. The zone or aureole of altered rocks surrounding a large batholith of granite may be a mile or more in width (see Fig. 79). Along the outer margin of this zone, clastic rocks begin to show more or less notable evidence of induration. In these indurated but otherwise unaltered rocks, the changes produced depend largely, as we have seen, on their mineralogical and chemical composition. Should the rocks be essentially argillaceous, aluminous silicates, such as chiastolite, often make their appearance, while at the same time biotite may be developed. Occasionally, when carbonaceous matter is diffused through a shale or slate this may become aggregated to form more or less abundant dark spots, and so give rise to one type of the rock known as *spotted slate* (see Plate XXII. 1). These carbonaceous spots disappear as metamorphic change increases and a schistose structure is superinduced. In other cases the spots take the form of concretionary knots, which seem to consist essentially of micaceous matter, cordierite, or andalusite. Knotted or spotted slates of this kind usually contain other new minerals, such as

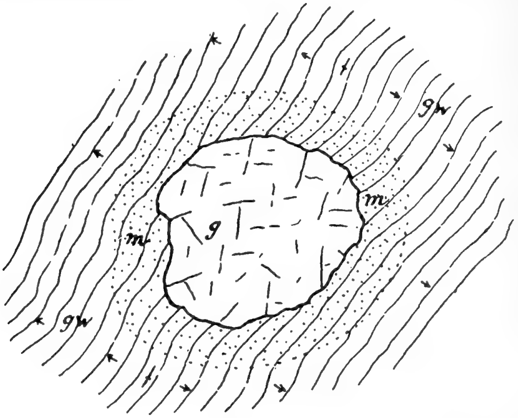


FIG. 79.—BATHOLITH WITH AUREOLE OF METAMORPHOSED ROCKS.
g, granite; *gw*, greywackés and shales; *m*, metamorphosed rocks.

quartz and mica, and as metamorphism advances, schistosity becomes more and more pronounced—the foliation being developed along pre-existing planes of division, as bedding or cleavage. Such a rock thus gradually merges into mica-schist or andalusite-mica-schist, often containing cordierite. This schistose rock in its turn eventually may become transformed, in close proximity to the batholith, into an exceedingly hard compact hornfels, in which no trace of schistosity may be observed.

In the aureole surrounding a batholith greywacké may undergo similar changes. Knots may be developed in them, and if the original rocks contained much felspathic matter, they may be transformed into rudely foliated or gneiss-like mica-quartz-rock, with cordierite in less or greater abundance. The metamorphism of sedimentary rocks being dependant on their chemical character it is obvious that the succession of changes witnessed in the neighbourhood of intrusive masses must vary with the varying nature of the surrounding rocks. Limestone, for example, is transformed into marble, through which new minerals are disseminated, such as tremolite, lime-garnet, idocrase, zoisite, and other lime-silicates. These new minerals doubtless represent the impurities (sand, clay) diffused through the original unaltered limestone. When they are very abundant the rock passes into *calc-silicate hornfels*. Pure siliceous sandy rocks are changed into quartzites and hard jaspideous schists; but should the original unaltered rocks have contained argillaceous matter, this is sure to be represented by the development of new minerals, such as mica. The molecular rearrangement of rock-ingredients and the chemical recombinations which result in the production of "new" minerals is one of the most notable phenomena of thermal and regional metamorphism alike. Equally noteworthy is the appearance of schistosity, which so frequently accompanies extreme rock-change. In thermal metamorphism, however, this structure is usually met with only in the immediate neighbourhood of a batholith, and it is not always present—the rocks in contact with an eruptive mass often appearing as highly compact, fine-grained, or coarsely crystalline rocks ("hornfelses") without any trace of foliation.

Schists and even igneous rocks, when they are traversed by batholiths, become metamorphosed, but the changes induced are less striking, and consist chiefly of recrystallisation and structural modifications. Schists, for example, may become highly contorted and puckered as they approach a batholith. Igneous rocks, likewise, are affected by plutonic intrusions—rearrangements and recombinations of their ingredients taking place, changes which are usually accompanied by the development of new minerals.

Not only are rocks of all kinds more or less metamorphosed by intrusive masses, but the igneous masses themselves are not infrequently affected by the rocks amongst which they have been intruded. Some remarkable examples have been cited by French geologists. In the Pyrenees, for instance, normal granite in contact with calcareous strata becomes hornblendic and passes into diorite, which may or may not contain quartz. In other places, where the surrounding rocks are not calcareous, the same granite is transformed into rocks of a still more basic character, such as norites and peridotites. Numerous xenoliths are scattered through the granite—all being metamorphosed and often passing by insensible gradations into the igneous mass that surrounds them.

It is believed that water has played an important rôle in thermal metamorphism. Deep-seated magmas probably contain large supplies of water and other vapours and gasses dissolved in them, the presence of which must increase the liquidity of the molten masses. Indeed, direct evidence of the existence of this contained water is supplied by volcanic phenomena, vast volumes of steam and vapours issuing from craters and escaping from lavas. Unaltered sedimentary rocks also contain considerable stores of water, for all are more or less porous, and are thus capable of retaining a larger or smaller proportion of interstitial moisture. In addition to this supply we must take note of the fact that many of the mineral constituents of rocks contain water in chemical combination. It is not surprising, therefore, that the more important metamorphic changes effected by a batholith are just such as should have been produced by steam permeating the rocks under great pressure and at a very high temperature. The steam has simply acted as a solvent menstruum, and has tended to produce a more or less perfect crystallisation or recrystallisation of the constituents of the rocks affected, leaving the chemical composition practically unchanged.

It is only generally true, however, that metamorphism has left the chemical composition of rocks unchanged. Not infrequently, silica has been introduced in abundance from batholiths, so as to permeate the contiguous rocks and to fill up cracks and fissures. The rocks of the metamorphic zone are thus frequently more or less abundantly traversed by smaller and larger veins of quartz, which in places may extend outwards almost to the very margin of the zone, but they rarely go beyond it. In some cases, these quartz-veins are accompanied by new minerals, the composition of which shows that they could not have been derived from the alteration of the surrounding rocks. Among the most interesting examples are the tin-bearing veins which are associated with intrusive masses of granite and other acid eruptives, and the apatite-veins which are more particularly connected with batholiths of gabbro. In the formation of the cassiterite-veins, various volatile fluorides, boron-compounds, etc., have taken part; for the tin-ore is usually accompanied by fluor-spar, schorl, etc. According to Professor Vogt, the contents of such veins were extracted from the granite before the plutonic mass had fully congealed. This is proved by the fact that the same series of elements which characterise the cassiterite-veins occur also in the pegmatite-veins of granite. In the case of the apatite-veins, analogous phenomena occur, the elements they contain being the same as those met with in gabbro. Thus, while potassium and lithium minerals are characteristic of tin-veins, magnesium and calcium-sodium minerals are notable constituents of apatite-veins. "In both classes of veins," Vogt remarks, "we find a characteristic pneumatolytic metamorphism of the country-rock. Each class has in abundance a halogen element, the tin-veins carrying fluorine (with a very little chlorine), and the apatite-veins chlorine (with a very little fluorine)." He concludes, therefore, that the materials of the apatite-veins have been extracted from the gabbro magma, just in the same way as the contents of the tin-veins have been obtained from granite. In the former case, an aqueous hydrochloric solution has been concerned in the extraction process, while in the latter case this process has been based chiefly upon a reaction in the presence of water of hydrofluoric acid dissolved in the granite magma.

Not improbably, many other veins, rich in ores of various kinds, which occur in close association with eruptive rocks, have originated in the same way as the tin-veins and apatite-veins. The veins referred to are usually independent of the character of the rocks they traverse, while a more or less clear genetic connection can be established between them and the eruptive masses. Moreover, the rocks in which they occur are always metamorphosed in a less or greater degree; they have obviously been permeated by mineralising agents, or subjected to a kind of solfataric action. (See further under "ORE-FORMATIONS.")

The following conclusions appear to be well established as a result of the study of Thermal or Contact Metamorphism:—

1. Rocks of all kinds are liable to become metamorphosed at their contact with eruptives—the nature of the changes depending partly on the chemical composition of the invaded rocks, and partly on the petrographical character and the volume of the intrusive masses.

2. Metamorphism has usually been effected without any marked alteration of the chemical composition of the rocks attacked.

3. In certain cases, however, highly heated solutions, derived from plutonic intrusions, have penetrated and permeated contiguous and surrounding rocks, and thus, by introducing new materials, have altered more or less considerably their chemical composition.

4. Crystallisation has been superinduced by metamorphism in derivative rocks, while igneous and schistose rocks have in like manner been recrystallised.

5. The production of new minerals is a common accompaniment of thermal metamorphism.

6. Now and again the rocks near their contact with a batholith may be rendered schistose, owing to the development of new minerals along pre-existing planes of division, whether planes of bedding, cleavage, or foliation.

7. The petrographical character of a batholith is sometimes considerably affected by that of the rocks it has invaded. Apparently this is due to the latter having been to some extent absorbed and assimilated by the intrusive mass.

(*b*) **Regional Metamorphism**. — There are extensive regions of schistose rocks where plutonic masses are so sparingly present that the metamorphism can hardly be assigned to their action. When gneiss, mica-schist, etc., are found occupying hundreds and even thousands of square miles, it is impossible to believe that such broad areas could have been affected by the more or less widely separated batholiths, sills, and dykes by which they are often traversed. Alteration on this extensive scale is known as Regional Metamorphism. There have been many speculations as to its cause or causes. Some geologists, indeed, are inclined to the view that regional metamorphism is only contact or thermal metamorphism " writ large," as it were. They hold it probable that, although intrusive rocks may appear at the surface only here and there throughout an extensive area of schistose rocks, nevertheless such an area may be underlaid at no great depth by vast plutonic masses. It is impossible to deny that this may sometimes or even often be the case. There can be no doubt that batholiths which show at the surface frequently extend laterally for long distances underground, and this is one reason for the extreme width sometimes attained by the aureole of metamorphic rocks surrounding a plutonic mass. It is probable, moreover, that the numerous veins and dykes which often crop out at a great distance from the visible margin of a granite mass are not directly connected with it, but with its underground extensions. Nevertheless, when throughout an extensive region of schistose rocks no batholiths appear, even in the deepest sections, while dykes are either absent or very sparingly present—we are not justified in assuming the existence of concealed plutonic masses to account for the general metamorphism. Cases of this kind call for a different explanation.

(a) *Plutonic Metamorphism.*—The earliest attempt to explain the phenomena in question was made by Hutton—the eminent Scottish geologist—who maintained that the crystalline schists were originally aqueous sediments which had been gradually deposited upon the floor of the ocean. When a great thickness of strata had accumulated, the loose sediments were supposed to have been consolidated by the pressure of the overlying masses. The internal heat of the earth next began to soften the compressed strata, and even eventually to melt them. The melted portions were thought to be now represented by granite, etc., while the strata which were only softened by the "internal fire," now formed our crystalline schists. The view held by Hutton and his followers still finds many supporters. But with our increased knowledge of the geological structure of the earth's crust, and of the chemical and physical conditions which have played their part in modifying rocks, it is needless to say that the views of plutonic metamorphism now maintained differ very considerably from those first enunciated by Hutton.

The changes which affect the crust superficially, as we have seen, are the result of weathering, and are brought about at ordinary temperatures and under atmospheric pressure only. But temperature and pressure gradually augment with increasing depth. At first they are both moderate, and water is plentifully present. Hence the chemical processes taking place in this upper zone might be expected to result in the formation of many common minerals, especially hydrates, such as hydrous-mica, chlorite, talc, etc., together with magnetite, quartz, calcite, etc. To this zone, therefore, should belong such rocks as hydro-mica-schist, phyllite, chlorite-schist, talc-schist, serpentine, quartzite, etc. At a greater depth the mineralogical changes must become more marked—among the metamorphic rocks developed in this second or middle zone, would be mica-schist, staurolite-schist and amphibole-schists, garnet-rock, mica-gneiss, hornblende-gneiss, marble, quartzite, etc. In the deepest zone under a very high temperature and excessive pressure the metamorphism ought to be correspondingly increased. Here, owing to the meagre presence of water, a general absence of hydrates might be expected—and the rocks most characteristic of this zone should be gneisses of various kinds (biotite-, augite-, sillimanite-, cordierite-gneiss), garnet-rocks, marble, quartzite, etc. In short, the metamorphism would gradually increase in intensity as the highly heated interior was approached. It is even conceivable that at the greatest depths the metamorphosed rocks might be melted.

Thus the theory of plutonic metamorphism does not, after all, differ essentially from that of contact metamorphism, for, according to the former, the heated interior of the earth seems to have played the same rôle as a batholith. If the theory in question were generally applicable, then it would follow that all rocks which have formerly been covered by a great thickness of overlying masses, and thus brought within the influence of a high subterranean temperature, ought to be more or less metamorphosed; while strata of relatively recent date, which never could have been thus deeply buried, ought to be free from any trace of metamorphism. As matter of fact, however, there are wide regions occupied by great successions of sedimentary rocks—the basement beds of which, owing to folding and subsequent denudation, are now exposed ; but although those lower beds must have been subject to the action of plutonic heat, they yet remain unaltered. On the other hand, much younger formations, which have not been concealed under any considerable thickness of rock, have nevertheless in some cases been highly metamorphosed.

Certain recent observations in Finland, by Dr J. J. Sederholm, would seem to show, however, that the old Huttonian view, as subsequently modified, may have greater significance than many geologists have recognised. Dr Sederholm sets forth certain remarkable evidence which has led him to conclude that wholesale "refusion or resolution" of certain pre-Cambrian rocks (consisting of granitoid gneisses with subordinate sedimentary strata) has actually taken place. According to him this melting process must have been effected at a time when these rocks were buried under a great thickness of rock-masses, removed since by denudation. The pre-Cambrian strata are believed to have been so deeply depressed that they approached the highly heated interior or "bottomless magma ocean" of the earth. Under such conditions, the rocks in question appear to have been largely melted or resorbed by the magma, and thus eventually transformed into crystalline granitoid masses. Through these are dispersed isolated fragments (xenoliths) of the original rocks which are often fused to such an extent that they are almost effaced.

(b) *Hydrochemical Metamorphism.*—In opposition to the views upheld by the supporters of plutonic metamorphism, Bischoff, in his famous work (*Chemical and Physical Geology*), maintained that high temperature and pressure were not required to account for the phenomena of the crystalline schists. He showed that water slowly percolating through the rocks would act as a reagent—breaking up minerals and inducing multitudinous recombinations, and that all the constituent minerals of schistose rocks could be produced in the wet way at ordinary temperatures. His conclusions were largely based on the study of pseudomorphs, which he had no difficulty in showing frequently occurred in rocks that gave no evidence of having been subjected to heat. One mineral could be altered into another either by the loss or the gain of an ingredient, or by the exchange of ingredients. Or there might be a total change of substance—the new mineral containing none of the ingredients of its predecessor. If this could be the case with crystallised minerals, similar changes must affect sedimentary rocks—out of clay, for example, all the minerals of gneiss might be developed by chemical reactions. The hydro-chemical theory is thus plausible enough, and explains many of the alterations which all rocks have undergone. Bischoff's work was of essential service, and must still be studied by geologists who are interested in the remarkable transformations which are brought about by the action of meteoric water making its way down from the surface. The theory fails, however, to account for regional metamorphism. If it were well founded, then all the oldest sedimentary formations should long ago have been metamorphosed, while the younger systems should never show any trace of such change. Yet we find that in many places the very oldest fossiliferous strata (Cambrian), although they must have been subject to the action of percolating water for untold millions of years, are nevertheless quite unchanged. On the other hand, strata belonging to relatively recent times (Tertiary) have in some places been rendered crystalline and schistose. Even if these contradictory facts could be reconciled or explained away, we should still be unable to explain the appearance presented by the schists themselves. These, as we have seen, are arranged in layers or beds of very different chemical and mineralogical constitution — mica-schist, for example, is found alternating with, but sharply marked off from, beds and layers of such rocks as hornblende-schist, talc-schist, gneiss, quartzite, serpentine, crystalline limestone, etc. Had the metamorphism of these rocks been caused by circulating water introducing and abstracting ingredients, as in the formation of pseudomorphs, there could have been no such arrangement of the schists as that referred to. The changes effected by percolating water would have been independent of bedding-planes, and would have been most in evidence along the more or less vertical joints and fissures by which the rocks are traversed.

(c.) *Dynamo-metamorphism.*—New light was thrown upon the origin of regional metamorphism, when it became recognised that the altered rocks were usually somewhat highly folded, and that the intensity of the metamorphism was in direct proportion to the degree of crustal deformation—crystalline texture and schistose structure becoming more and more pronounced as the centres or axes of greatest disturbance were approached. It was observed that in the areas of greatest disturbance highly crystalline and puckered schistose rocks predominated, and that as one passed outwards from such areas, rocks of that type gradually gave place to others in which crystalline texture and foliated structure became less and less prominent, and at last died away as flexing, folding, and rock-displacements continued to diminish in importance.

The effects produced by this dynamo-metamorphism resemble in some respects those brought about by thermal metamorphism. In both cases alike, the changes have as a rule left unaltered the composition of the rocks attacked. Clastic rocks, owing to recombinations of their ingredients, have been rendered crystalline, while igneous and old schistose rocks have in like manner been recrystallised. In other respects, however, there are notable differences to be observed between the two kinds of metamorphism. In regional metamorphism, for example, we have no evidence of actual fusion, such as occurs now and again in the case of thermal or contact metamorphism. On the other hand, in contact metamorphism there is little to show that the altered rocks have been concurrently subjected to much lateral pressure, whereas the rocks throughout an area of dynamo-metamorphism give proof of having experienced the most intense compression. Again, in the case of contact metamorphism, foliation when present always coincides in direction with pre-existing planes of division, while in that of regional metamorphism such coincidence is more or less accidental, foliation having been developed usually along planes of compression. In steeply folded rocks, therefore, foliation sometimes coincides with original bedding-planes, or it may cross these at any angle. Owing to metamorphism, however, the original rock-structures are often wholly obliterated, and it is then impossible to say what influence these may have had in determining the direction of foliation. Along great thrust-planes the immediately adjacent rocks are often rendered crystalline and schistose, and in such cases the foliation coincides in direction with the plane of rock displacement.

Slaty Cleavage.—In a preceding chapter (p. 141) the phenomena of rock-folding were discussed, and it was there pointed out that the constituent ingredients of a folded rock were often more or less deformed or distorted. Deformation of the kind referred to is often conspicuously developed in areas of dynamo-metamorphism, more especially along their outer margin. In this peripheral zone the rocks may be arranged in more or less steeply inclined positions, but they are neither crystalline nor foliated. Nevertheless they usually afford evidence of having been compressed. This is shown by the superinduced structure known as *Slaty Cleavage*, a structure which renders a rock capable of being cleaved or split into slabs, plates, or laminæ in a direction independent of the planes of bedding. When such a rock is examined under the microscope, the particles of which it is composed are seen to be flattened out in one and the same direction —an arrangement which obviously accounts for the fissile character of clay-slate. A rock of this kind, therefore, cleaves or divides most readily along planes of compression, and not, as in the case of shale, along planes of deposition. That slaty cleavage is one of the concomitant results of crustal deformation is shown by the fact that the planes of cleavage are always parallel to the axes of anticlinal and synclinal folds. When the structure is well developed, not only does the original lamination disappear, but even the planes of bedding may be rendered obscure or altogether obliterated. Cleavage may intersect the bedding-planes at any angle, or may now and again coincide with these where the limb of a fold is inclined in the same direction and at the same angle as the planes of compression (see Plate XLIX.). Slaty cleavage is best developed in fine-grained, homogeneous clay-rocks, which are sometimes so fissile that they divide with ease into very thin smooth plates. It is not confined, however, to

CLEAVAGE IN STEEPLY-FOLDED SLATES AND PHYLLITES, NEAR CARRIG NAM FEAR, ISLAY.

Photo by H.M. Geological Survey.

[*To face page* 224.

argillaceous strata, but may affect rocks of the most diverse character, as greywacké, conglomerate, and crystalline eruptives; but in such rocks it is never well developed, the planes of cleavage being usually imperfect and more or less irregular and discontinuous.

Although the clastic character of ordinary clay-slate is sufficiently obvious, the rock is nevertheless not quite devoid of all crystalline structure. Now and again the surfaces of the cleavage-planes show scales of mica and needles of rutile, and such indications of incipient metamorphism gradually increase as the centre or axial zone of a much disturbed region is approached, with the result that clay-slate merges into phyllite. Followed in the same direction, phyllite in its turn passes into mica-schist, while the foliation of the latter may become more and more puckered and crumpled as the contortion of the rocks increases. Finally, the mica-schist may merge into a gneiss.

The changes involved in the passage of a clay-rock through the several stages of slate, phyllite, schist, and gneiss are obviously partly mechanical, partly chemical. No doubt the rocks undergoing deformation would be more or less deeply buried, and subject therefore to the pressure of overlying masses and possibly also to the action of the internal heat of the earth. However that might be, it is obvious that while the process of flexing and folding was going on, heat would necessarily be evolved and continue to augment as compression increased. The ingredients of the rocks would be mechanically crushed and flattened, while at the same time chemical action would be stimulated, and in the presence of water recombinations of the rock-materials would be effected—the minerals thus formed being arranged with their longer axes parallel to the planes of compression. Clay-rocks, composed as they are of fine-grained and relatively soft ingredients, would naturally offer least resistance to compression—cleavage-structure would, in their case, be readily superinduced. On the other hand, coarse-grained rocks, whether clastic or crystalline, would not be so readily affected. Their constituents being individually larger and usually more resistant than those of an argillaceous rock, a greater degree of pressure would be required to crush and flatten them. Hence it is that coarse-grained beds interstratified with clay-slates often show little or no trace of change beyond mere induration. When such coarse-grained rocks, however, are followed towards the zone or centre of greatest disturbance, they all eventually yield and become cataclastic. The rounded stones of a conglomerate and the angular fragments of a breccia, for example, are crushed, flattened, and elongated until they appear as mere lenticular streaks or cease to be recognisable, stones and matrix together being converted into a mylonite or into a crystalline schistose aggregate. Granitoid crystalline rocks are in like manner crushed down, recrystallised, and foliated. Not infrequently, in such crushed eruptives, lenticular cores (or *phacoids*, as they are termed) of the original rock can still be observed, around which the finely pulverised and recrystallised materials are arranged much in the same way as the smaller crystalline ingredients of a lava have grouped themselves about a phenocryst. All the phenomena, in short, conspire to show that the metamorphosed rocks in question have been so compressed and crushed that they have been compelled to flow.

Just as in thermal or contact metamorphism the rocks become increasingly affected as a plutonic mass is approached, so also in regional metamorphism we encounter gradually augmenting rock-changes while we proceed from the peripheral areas of comparatively unaltered rocks to the entirely reconstituted masses of the interior region. Advancing towards the latter region we first encounter, it may be, slates, phyllites, hydrous mica-schists, chlorite-schists, serpentine, diabase-schist, green schists, conglomerate-schists, and other rocks similarly indicative of less intense metamorphic action. Next we enter a region, the most characteristic rocks of which are andalusite-, kyanite-, and staurolite-schists, mica- (muscovite, biotite) schists, amphibole-schists and amphibole-rock, granulite, gneisses (usually fine-grained), etc. Reaching the inner zone, we are confronted with coarse biotite-schist, frequently containing garnets, granulite, eclogite, biotite-garnet-gneisses (often coarse-grained), hornblende-gneiss, amphibolite, etc. Quartzite, crystalline limestone, and calc-mica-schist may be present on any horizon.

Here, then, we have much the same succession of changes as are supposed to have occurred in the case of plutonic metamorphism. And upholders of the latter theory would probably claim such a succession as favouring their own view. The present folded and crumpled aspect of the schists, they might say, were the result of subsequent crustal deformation.

The theory of dynamo-metamorphism explains so many striking phenomena which are hard to account for by the plutonic theory that it is accepted by many geologists as giving a reasonable interpretation of regional metamorphism as a whole. Nevertheless there are difficulties in the way of accepting it as generally applicable. For example, in many places the highly convoluted strata of certain mountains of uplift show no evidence of true metamorphism—the petrographical character of clay-slates, greywackés, sandstones, and limestones has remained unaffected during the process of compressing and folding. Again, there are regions where highly crystalline schists occupy undisturbed positions —that is to say, they are not plicated or folded. Once more, it has been shown that the process of metamorphism has in some cases preceded that of rock-folding.

The probabilities are that metamorphism is the result sometimes of contact with batholiths or even with the heated interior of the earth, and sometimes to the strains and stresses due to crustal movements. Occasionally thermal and dynamo-metamorphism may have acted together, and in such cases it may be impossible to say which of the two processes has played the dominant rôle. In both pressure is recognised as an important factor, and the presence of water, either in the liquid or the gaseous form, is another essential condition—water itself acting as a mineralising agent and carrying with it various other chemical agents of change. But the phenomena of slaty cleavage, and the cataclastic structures so frequently met with amongst crystalline schists are clearly the result of compression and crushing, and can only be explained by the theory of dynamo-metamorphism. Even schistose structure on the large scale can hardly be accounted for without pressure. The metamorphism of rocks, however, is still far from being satisfactorily explained. Geologists are much divided in opinion, and many observations and much research, as well chemical and physical as geological, will be required, before an adequate conception of the subject can be attained.

Archæan Rocks.—Under this head are included a remarkable group of coarsely crystalline gneissose rocks, the origin of which has been a fruitful subject of discussion. The rocks in question, although termed gneiss, are not truly schistose rocks. They show a banded structure, indeed, but this cannot be confounded with foliation, but is suggestive rather of a kind of fluxion-structure. The bands in question somewhat resemble those streaky layers and veins so commonly present in certain massive eruptive rocks. The constituent minerals of the layers referred to seem to have segregated either while the igneous rock was in motion or after it had ceased to move. The gneissose rocks, moreover, ever and anon lose their banded structure, and merge into massive rocks, which cannot be distinguished from granitoid eruptives. Not only so, but they frequently behave as intrusive rocks, one gneiss cutting across another. These and other appearances lead to the belief that the Archæan granite-gneisses are of igneous origin. They underlie the oldest stratified rocks of the globe, wherever the base of these is exposed, and hence are thought by some geologists to represent the original crust formed upon the surface of the globe. They vary much in composition—from highly acid to highly basic. In some places they appear to alternate with truly schistose rocks and crystalline limestones, as if all belonged to one and the same series. This appearance, however, is perhaps deceptive, and due to the intrusive character of the gneisses. It may be added that almost everywhere the Archæan rocks yield evidence of having been subjected to powerful deformation—they have frequently been crushed, pulverised, recrystallised, and foliated.

CHAPTER XVI

ORE-FORMATIONS

Syngenetic Ore-Formations—Native Metals and Ores in Igneous Rocks; Ores in Bedded Rocks (Chemical Precipitates, Clastic Ores, Ores in Schists). Epigenetic Ore-Formations—Fissure Veins or Lodes; Nature of Fissures; Width and Extent of Lodes; Simple and Complex Lodes; Transverse and Coincident Lodes; Systems of Lodes; Branching and Intersection of Lodes; Heaving of Lodes; Contents of Fissure Veins; Structure of Fissure Veins; Outcrop of Lodes; Gossans; Association of Ores in Lodes; Succession of Minerals in Lodes; Walls of Lodes; Stockworks.

ORES are metalliferous minerals or mixtures of such minerals, in which the proportion of metal is often sufficiently large to admit of its being profitably extracted. The term "metal" is here used in a conventional (not in a chemical) sense, and does not, therefore, apply to the metals of the alkalies and alkaline earths, but only to the "heavy" metals of commerce, viz.: gold, silver, platinum, copper, tin, lead, zinc, iron, manganese, nickel, cobalt, chromium, mercury, antimony, bismuth, etc.

Classification.—As one kind of ore-formation frequently passes into another, while considerable doubts obtain as to the genesis of many ores, it is hardly possible to devise a scheme of classification to which exception cannot be taken. For purposes of description, however, ore-formations may be grouped under these two main divisions:—1. **Syngenetic** or **Contemporaneous,** and 2. **Epigenetic** or **Subsequent.**

I.—SYNGENETIC ORE-FORMATIONS

These are formations of the same age, broadly speaking, as the rocks in which they occur or with which they are immediately associated. Some of them appear in igneous rocks, while others are associated with derivative, and yet others with schistose, rocks.

I. ORES OCCURRING IN IGNEOUS ROCKS

Ores of this class are original or primary constituents, appearing sometimes as isolated grains or crystals, disseminated through the body of a rock; at other times, as larger or smaller aggregates or masses which have obviously separated out from a molten magma. Not only ores but native metals occur under these conditions, more especially in plutonic basic igneous rocks. Acid plutonic rocks, on the other hand, are seldom rich in such constituents.

(1) **Native Metals.**—Iron is irregularly disseminated through the basalt of Ovifak (Disco Island, West Greenland) in the form of scales, grains, nodules, and larger lumps and masses. Nickel-iron, in small grains, is met with in peridotite and serpentine in South Island (New Zealand). Platinum also occurs in similar small grains in peridotites, olivine-gabbros, and certain syenitic rocks in the Ural Mountains, and in peridotite in British Columbia. Gold, silver, copper, etc., have likewise been detected, generally as minute inclusions, in the constituent minerals of various igneous rocks—never in sufficient quantity, however, to invite mining operations.

(2) **Ores.**—These are oxides and sulphides—the former being represented chiefly by magnetite, ilmenite, and chromite; and the latter by pyrite, pyrrhotite, and chalcopyrite—each of which may contain variable percentages of nickel and cobalt.

Oxides.—Magnetite, often titaniferous, is one of the commonest and most widely diffused constituents of igneous rocks. Now and again it forms massive aggregates in plutonic basic eruptives, as in certain gabbros, and gabbro-diorites in Sweden, Finland, Norway, and North America. In these rocks the mineral occurs disseminated in the usual way, along with other accessory constituents, but is so abundant as sometimes to constitute a large percentage of the rock. Here and there, indeed, it becomes concentrated so as to form enormous aggregates. In some cases these aggregates are sharply marked off from the igneous rock in which they lie; in other cases, the disseminated ore gradually becomes more and more abundant at the expense, so to speak, of the other constituents of the gabbro, so that there seems to be, as it were, a passage from the latter into the ore-aggregate. Such aggregates are usually rich in ferromagnesian minerals (hornblende, rhombic pyroxene, and olivine), which are not infrequently accompanied by biotite, apatite, green spinel, and various sulphides (pyrite, pyrrhotite, and chalcopyrite).

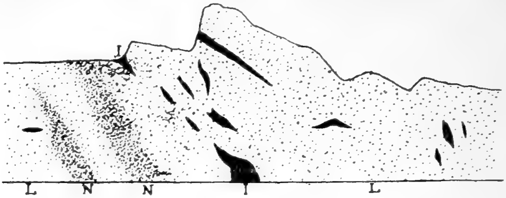


FIG. 80.—SECTION AT BLAAFJELD. (Vogt.)
L, Labradorite-rock; N, Norite-pegmatite; I, Ilmenite. Length of Section 600 metres.*

Ilmenite (titaniferous iron-ore) occurs in some Norwegian gabbros under similar circumstances (Fig. 80), the ore-aggregates either forming an abrupt junction with the mother rock or graduating into it in the same way as titaniferous magnetite. Chromite is a frequent constituent of peridotites, and now and again so largely abounds that the rock containing it is mined. At Hestmandö, in Norway, for example, the rock exploited is composed essentially of olivine, enstatite, picotite, and chromite. Tin-ore (cassiterite) likewise occurs as a primary constituent of many granites, but only in scattered grains and thin veins.

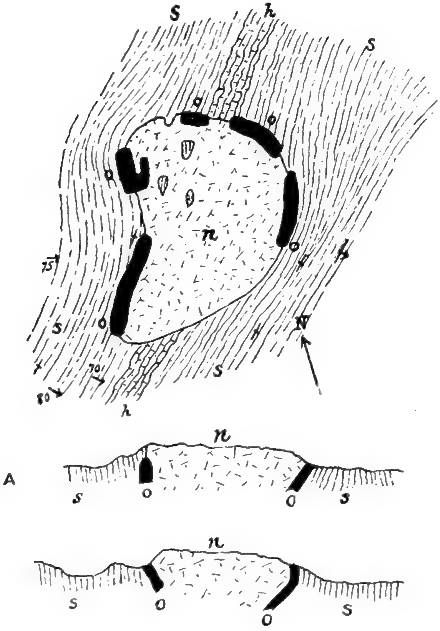


FIG. 81.—SKETCH-PLAN OF MEINKJÄR, NORWAY. (After Prof. Vogt.)
s, gneissose rocks; *h*, hornblende-schist; *n*, norite with inclusions of gneiss (xenoliths); *o*, ore; A, B, sections across the area, from east to west.

---

* The Labradorite-rock (gabbro) contains some 2 per cent. ilmenite, 4 per cent. ferromagnesian minerals, and 94 per cent. felspar; the Norite-pegmatite yields 40 per cent. ilmenite, 35 per cent. ferromagnesian minerals, and 25 per cent. felspar. Where the Norite-pegmatite graduates into the Labradorite-rock, the percentages are as follows:—6 to 18, ilmenite; 8 to 16, ferromagnesian minerals; and 56 to 66, felspar.

It has never been mined in these rocks, but this is probably one of the sources of the tin-ore of "placers."

Sulphides.—Pyrite and pyrrhotite appear now and again as ingredients of certain igneous rocks, and chalcopyrite has also been recorded as occasionally occurring under similar conditions. While, in some cases, such metallic sulphides may be of secondary origin, there seems no reason to doubt that they are frequently primary constituents of the rocks in which they appear. It is highly probable, therefore, that the massive aggregates of sulphide ores met with in certain plutonic rocks are examples of magmatic segregation, and as truly syngenetic as the magnetic and titaniferous iron-ores referred to above. In some of the Norwegian gabbros, pyrrhotite, pyrite, and chalcopyrite, each containing a variable percentage of nickel and cobalt, are disseminated in small grains through the rock, but now and again they have segregated to form large masses of irregular form, which are grouped chiefly along the line of junction between the gabbros and the adjacent rocks (see Fig. 81). Similar examples of the magmatic segregation of nickeliferous sulphide-ores are met with in Sweden, Piedmont, and North America. It is believed by some authorities that the auriferous pyrite of Rossland, British Columbia, and the high-grade copper-ores occurring in the peridotites and serpentines of northern Italy have originated in the same way.

2. Ores occurring in Bedded Rocks

Under this head are included precipitates from aqueous solution, certain alluvial deposits, and ores interstratified with crystalline schists.

(1) **Precipitates from Aqueous Solution.**—The most important ores of this origin are iron- and manganese-ores. The iron-ores in question are well represented by the formations which are taking place now in marshy land and lakes. These consist essentially of hydrated ferric oxide, but usually contain many impurities. Sometimes they form continuous beds; in other places they occur as nodular concretions of some size, or as aggregates of oölitic and pisolitic spherules. They are the products of the alteration of ferriferous minerals and rocks, and owe their origin mainly to the action of water containing organic acids, which act as powerful solvents of iron-salts. Rocks exposed to the action of such acidulated water are bleached white by the removal of their iron, which is carried away in solution as a bicarbonate. From this solution, the iron tends to be precipitated as ferric hydrate, unless much decomposing organic matter be present; when such is the

case oxidation is prevented, and the iron is then thrown down as a carbonate. The pisolitic limonite forming in the shallow waters of many existing lakes, and the earthy bog iron-ore so frequently present in swampy land, are good examples of this class of ore-formations. Bedded iron-ores (both oxides and carbonates) are met with in many geological systems—ranging from post-Tertiary to Palæozoic horizons. While many of these are of freshwater or brackish-water origin, others are marine. As examples may be cited the iron-ore of Rio Tinto, in the province of Huelva, Spain—a deposit of Recent age; the Mesozoic limonites and earthy carbonates of the Lias, the Great Oölite, the Wealden, and the Lower Greensand, in England; and the clay-ironstones which are so abundantly developed in the Carboniferous system of this and other countries (Fig. 82). Most of the ironstones last referred to appear to have been formed by direct precipitation in lakes and lagoons. In the case of the nodular concretions met with in the same series of strata, we have examples of the subsequent concentration or aggregation of ferruginous matter, originally diffused through the beds in which such nodules occur.

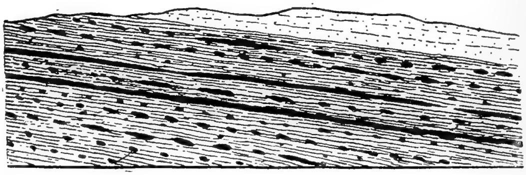


FIG. 82.—SEAMS AND NODULES OF CLAY-IRONSTONE IN CARBONIFEROUS SHALES.

Manganese ores (pyrolusite, psilomelane, wad) are not so abundantly met with as iron-ores. They occur, however, under similar conditions amongst sedimentary rocks of all ages, sometimes as concretionary nodules, at other times in layers and beds, which are not infrequently pisolitic.

(2) **Clastic Ore-Formations.**—These are alluvial deposits, derived from the disintegration of metalliferous rocks and ore-bodies of various origin, and are known to mining men as *Placers* (Fig. 83). The metals obtained from such deposits are chiefly gold, platinum, and tin. The beds vary much in

character, consisting, in some places, of coarse gravel and shingle, or of finer gravel, grit, and sand. Most placers are of Recent and Pleistocene age, and are usually more or less unconsolidated. Many, however, occur in the Tertiary system, while a few date back to Mesozoic, and some even to Palæozoic times. These older deposits are, as a rule, consolidated, forming coarse grits and conglomerates. The metals and ores of highly porous placers are usually concentrated in the bottom layers. In the case of finer grained alluvia, however, they may be sparingly scattered through the whole thickness of the deposits. Should the bed-rock underlying a placer be more or less fissured and shattered, the metal or ore not infrequently finds its way down for a few inches into cracks and crevices. While the gold occurring in quartz-veins, etc., is often intimately associated with metallic sulphides, such as iron-pyrite, the gold met with in placers is usually in the free state. During the processes of disintegration and denudation, the sulphides containing the gold are gradually dissolved, and the process of solution is carried on in the placer itself, so that sooner or later the gold becomes freed from its baser associates. The crystalline surfaces occasionally presented by placer-gold, and the usually smooth and unscratched appearance of the nuggets, are suggestive of chemical deposition. Many mining men, indeed, believe that nuggets grow by slow accretion.

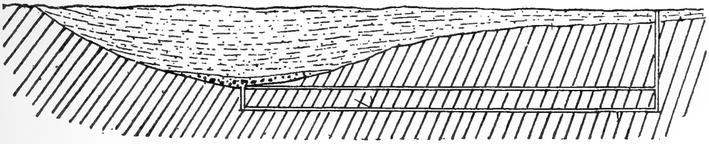


FIG. 83.—SECTION OF AURIFEROUS LEAD (OR PLACER) ON THE LOWER MURRAY, NEAR COROWA. (After E. F. Pittman.)

Placers being of fluviatile origin, it will be readily understood that such formations can seldom be of great geological antiquity. Terrestrial accumulations are only exceptionally preserved—the Mesozoic and Palæozoic systems consist for the most part of marine formations. The further back we trace the geological record, therefore, the scantier become all traces of old land-surfaces. Lacustrine and fluviatile deposits of Tertiary age have now and again been preserved, under lava, as in California and Victoria (Australia). The auriferous gravels of these regions are believed to be river-gravels belonging to the Pliocene. They are often more or less hardened by infiltration of silica, ferruginous matter, etc., and constitute the "deep leads" of the miners. The shallow placers of the same regions are of recent age—derived in considerable measure from the denudation of the older series. The alluvial deposits of the Ural Mountains, which yield both gold and platinum, the "stream-tin" (cassiterite) accumulations of Cornwall, which are now practically exhausted, and the alluvial tin-fields of Malaysia, from which three-fourths of the world's output at present come—are all examples of the same class of ore-formations. Placers of older date than the Tertiary are of rare occurrence, only a few gold-bearing conglomerates having been met with in Mesozoic and Palæozoic systems, and these are seldom rich enough to be worked.

(3) **Ores occurring in Schistose Rocks.**—Ores of iron and manganese are the most frequently occurring formations met with as beds interstratified with schistose rocks. It is sometimes difficult to distinguish such syngenetic formations from certain epigenetic formations which are known as "bedded veins," and of which some account is given in the sequel. Usually, however, a bedded ore is not so sharply marked off from the schists among which it lies, as is the case with a true vein. The bedded ore does not traverse overlying and underlying schists, nor does it send out veins. It behaves, in short, like a truly contemporaneous bed—following all the flexures, folds, and crumplings of the series in which it occurs. The thickness of such beds varies indefinitely: they are usually lenticular, and thicken and thin out irregularly. From a few inches, they may gradually swell out to many feet or even yards. The thickest bed of ore yet encountered is that of Grängesberg in Sweden, which is not less than 100 yards. In that country the bedded ores are usually more or less closely associated with crystalline limestone, or with a rock consisting mainly of pyroxene and amphibole, and often containing garnet and epidote. Iron-ores are obtained from similar schistose rocks in Norway.

In Dunderlandstal, for example, they occur in numerous beds (sometimes as many as 500), rapidly interstratified with mica-schist, and closely associated with massive beds of crystalline limestone and dolomite, from which, however, they are always separated by a variable thickness (1 to 10 metres) of mica-schist (Fig. 84). This ore belt has been followed continuously for a distance of several miles. It varies much in width, sometimes showing a thickness of 30 to 60 metres, and even exceptionally 75 to 100 metres, but more usually ranging between 3 to 10 metres. The ore is a fine-grained mixture of specular iron, magnetite, and quartz, with various silicates—the proportion of specular iron being double that of magnetite. Usually the iron-ore is scaly, and has the character of an iron-mica-schist. The minerals associated with this ore are chiefly epidote, garnet, and hornblende, also a little mica, felspar, etc., together with scattered microscopic granules of calcite. It may be added that the ore contains small percentages of manganese and phosphoric acid (=about 1 per cent. apatite). According to Professor Vogt, these remarkable ore-beds are undoubtedly interstratified with the schists, and occupy a definite geological horizon in the series. Throughout their whole extent they have a similar chemical and mineralogical constitution. They have no genetic connection with plutonic intrusive masses—the schists among which they occur are the result of regional, not of thermal or contact, metamorphism. The mica-schists are obviously metamorphosed sedimentary rocks—clay-slates or shales; the ores, on the other hand, which are always sharply marked off from the schists, could not have been originally mechanical sediments of quartz-sand and magnetite-specular-iron-sand, seeing that they contain a somewhat constant and relatively high percentage of phosphoric acid. Professor Vogt has no doubt, therefore, that the ores were originally chemical precipitates, probably formed much in the same way as the iron-ores now accumulating in many lakes and bogs. This explanation is in keeping with the frequent occurrence of petroleum, mineral pitch, and anthracite in the schistose rocks with which such ore-beds are associated. Further, the lenticular form assumed by many of the ore-formations is possibly suggestive of their deposition in lacustrine hollows. The frequent occurrence of phosphoric acid and manganese in the ores are, according to Vogt, readily accounted for. Just as the iron must have been derived from the breaking-up of iron-rich minerals (augite, hornblende, etc.), so

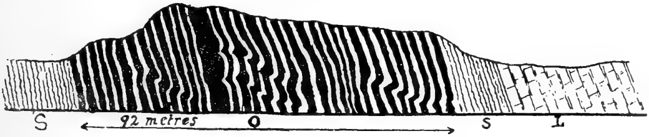


FIG. 84.—SECTION ACROSS ORE-BEARING SCHISTS, URTVAND IN DUNDERLANDSTAL, N. NORWAY. (After J. H. L. Vogt.)

S, schists; L, limestone; O, bands of iron-ore with intervening schists.

the phosphoric acid would be obtained from apatite (common as a constituent of igneous rocks) and the manganese from many different rock-forming minerals. We may suppose that regional metamorphism would bring about marked changes in the original chemical and mechanical sediments. What were at first carbonates and hydrates of iron would, under the influence of heat in the presence of moisture, eventually be transformed into specular iron and magnetite, while the clays associated with them would be changed into mica-schist.

Beds of magnetite and specular iron are associated with schistose rocks in many other countries, as in S. Russia, in the Riesengebirge, in Spain, in the United States (New York, New Jersey, Carolina, Michigan), and elsewhere. Carbonate of iron (siderite) is another ore met with amongst schistose rocks. At Hüttenberg, in Carinthia, it occurs in crystalline limestones which are interstratified with gneiss and mica-schist (see Fig. 85). Manganese ores likewise occur under similar conditions in Sweden, Bukowina, Brazil, and the United States of N. America.

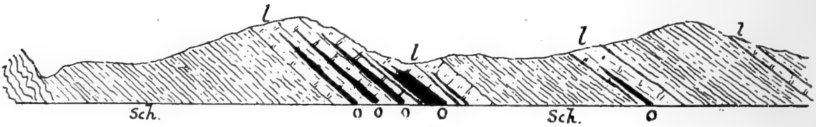


FIG. 85.—SECTION ACROSS THE ORE-BEARING ROCKS OF HÜTTENBERG IN CARINTHIA. (After F. Seeland.)

sch, schistose rocks; *l*, limestones; *o*, bands of iron-ore.

II.—EPIGENETIC ORE-FORMATIONS

The formations included under this head are of later age than the rocks with which they are associated or in which they occur. They have been subsequently introduced into the positions they now occupy, and thus a large number appear in fissures and other cavities in rocks of all kinds, while in many cases they replace pre-existing minerals and rock-masses. They may be grouped as fissure-veins or lodes, bedded veins, and irregular formations. This is not a very satisfactory classification, for one and the same ore-deposit may assume many different forms in its course, appearing sometimes as a "lode," sometimes as a "bedded vein," or as one or other of the "irregular formations." Nevertheless, the classification here adopted serves to bring prominently into view the various conditions under which the epigenetic ore-formations occur.

I. FISSURE VEINS OR LODES

Nature of Fissures.—An ore-vein or lode may be defined as a rent or fissure filled with metalliferous and other minerals alone, or with rock-débris in addition. The fissures in which true lodes occur are often mere chinks or wider clefts, along which no rock-displacement may have been effected. Narrow fissures of this kind may occur singly, but often quite a large number, occupying parallel or nearly parallel positions, traverse the rocks in some given direction. None of these may show slickensides or yield any evidence of slipping or faulting. Not infrequently, however, the fissures occupied by lodes are faults, although it would seem that the amount of rock-displacement (when that can be measured) is seldom very great—not often exceeding two or three hundred feet, and being usually much less. Many ore-bearing faults, however, traverse highly disturbed and schistose rocks, and the amount of displacement in such cases must be quite conjectural. Be that as it may, it would appear that the larger dislocations occurring in a region rich in lodes are seldom ore-bearing. The faults occupied by lodes may be normal or reversed. Few lodes are quite vertical, but the great majority approach verticality—the inclination from the vertical being termed the *hade* or *underlie*. The rocks traversed by a lode are known as the *country* or *country-rock;* and the wall of the fissure which overhangs the miner when standing upright is termed the *hanging-wall;* while that on which he stands is the *footwall* (see Fig. 86).

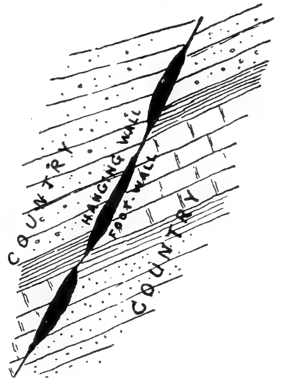


FIG. 86.—FISSURE-VEIN OR LODE.

Width and Extent of Lodes.—Individual lodes often vary much in width—the walls of the fissure approaching and receding in an irregular manner, and now and again being in close apposition, in which case the lode is, of course, "nipped out." Such irregularities, it need hardly be said, are due to the character of the original fissure, except when limestone forms the wall or walls of a lode. In such cases the irregular width of the cleft has not infrequently been caused by the unequal dissolution of the rock. Some lodes are very narrow—a few feet or less—others may exceed 100 feet in width. In the case of very broad lodes, however (say, from 20 feet to 100 feet), it must be understood that this is not the actual width of the original fissure, but includes as much of the adjacent rock as contains ore in payable quantity—whether occurring as impregnations or as strings, threads, veinlets, and *flats* (see pp. 252, 255). Some broad lodes, for example, consist of more or less numerous and approximately parallel veins, occupying very narrow fissures or mere cracks, which in the central portion of the "lode" are often less than an inch apart, but become more widely separated towards the limits of the fissured area. Lodes of this kind are known as "sheeted zones," and sometimes attain a width of 100 feet or more. A "sheeted zone," therefore, is simply a belt of highly fissured rock, which, when gold is present in the fissures, may be profitably extracted so long as the veins are rich enough or sufficiently numerous.

Lodes differ considerably in length or lateral extent. Some die out in much less than a mile, while others have been followed for great distances. Probably the longest known is the auriferous "Mother Lode" of the Sierra Nevada, California, which runs in a relatively straight line for more than 70 miles.

The longest veins seem usually to have the greatest vertical range. Some of these have been followed to depths not far short of 3000 feet, without showing any appearance of dying out. Many of the shorter veins wedge out downwards or upwards. Lodes of this kind are frequently very irregular—branching often in many directions. Some wedge out simply; others, again, divide into two or more smaller and gradually diminishing veins; or they may break up into a perfect network of strings and veinlets.

The actual depth to which the most persistent lodes may descend is not known. From several considerations, however, it may be inferred that the fissures occupied by lodes must in many cases have traversed a very great thickness of rock. Since those fissures were formed there has been excessive denudation, whereby a thickness of rock, to be measured in some cases by thousands of feet or even of yards, has been removed. Hence the present surface where such lodes crop out is very far below the surface that existed when the fissures were being filled with their ore-formations. In the case of certain lodes which have been mined to a depth of 1000 yards, it has been estimated that the original surface may have been 2000 or even 4000 yards higher than the present, which would give an original vertical range of 3000 or 5000 yards at least for the lodes.

It is doubtful, according to some, whether any cavities could be formed, or, having been formed, could remain open under the enormous pressure of 15,000 feet of rock. Others, again, have questioned the possibility of chemical precipitations from aqueous solutions taking place at such depths, where the pressure must be excessive and the temperature considerably above that of boiling water. But, as Vogt has pointed out, mineral deposits have certainly been made from solutions at a much higher temperature than is likely to obtain at a depth of 15,000 feet below the surface. He instances the occurrence of cassiterite, topaz, tourmaline, apatite, and other minerals in the pegmatite-veins of granite, which, having been abstracted from the granite magma, must have been deposited from solutions at a higher temperature than the critical temperature of water—690° F. or thereabout.

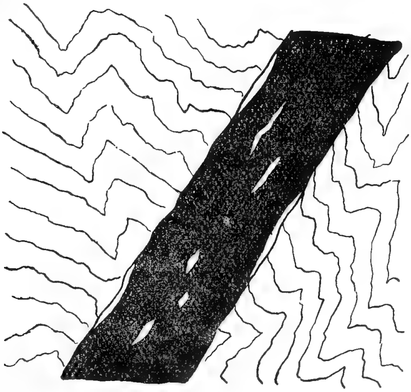


FIG. 87.—SIMPLE LODE SHOWING MASSIVE STRUCTURE.

As vertical fissures of all kinds tend to die out upwards, while the amount of displacement caused by faults diminishes in the same direction, we may infer that many fissures may never have reached the surface at the time of their infilling, the outcrops we now see having been exposed by denudation.

Simple and Complex Lodes.—A lode is said to be *simple* when it occupies one single well-defined fissure (see Fig. 87). Often enough, however, the formation of a fissure has been accompanied by much rock-shattering, the adjacent rocks being confusedly jumbled and crossed in every direction by numerous branching cracks and crevices. When all these cavities are filled with mineral matter we have a *complex* lode (see Fig. 88). One and the same lode may be simple in one part of its course and complex in another. This is not infrequently the case when a lode traverses rocks of very different kinds. For example, a vein may be simple while passing through rocks which have yielded readily to tension, but becomes complex when it begins to traverse some massive irregularly jointed rock (see Fig. 89).

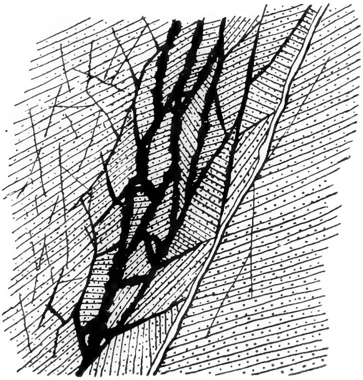


Fig. 88.—Complex Lode. (After R. Beck.)

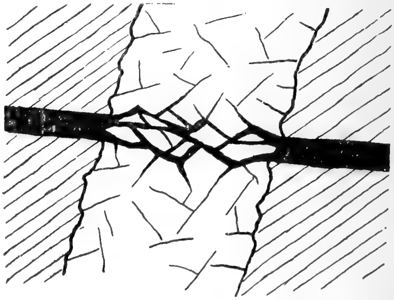


Fig. 89.—Lode dividing and branching in Igneous Rock. (Plan.)

Transverse and Coincident Lodes.—Lodes cutting through stratified rocks usually cross the planes of bedding at an angle, and are then said to be *transverse* (see Fig. 90). Now and again, however, especially when the strata dip at a high angle, a lode may coincide with the planes of bedding. The epigenetic character, however, is usually apparent, the lode not being strictly confined between two bedding-planes, but here and there invading both overlying and underlying strata (see Fig. 91).

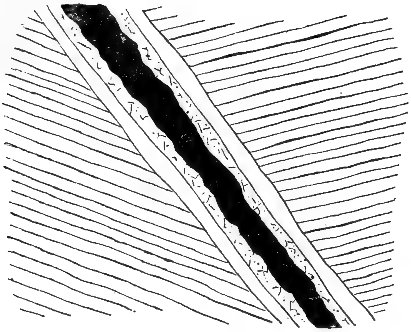


FIG. 90.—TRANSVERSE LODE. (After R. Beck.)

Systems of Lodes.—While lodes often occur singly, it is more frequently the case that several or many are associated so as to form one or more systems. Their general disposition recalls that of the basalt-dykes described in Chapter XIV. Like these, they trend in certain definite directions, some appearing in true faults, others in simple rents or fissures. In certain regions only one such system may be present; in other places two or more systems may appear, one set crossing another. As the fissures and faults in which they occur are the result of crustal movements, it is not surprising that groups of parallel lodes should often bear a definite relation to the principal folds and flexures of a region. Some, therefore, coincide with the average strike of the country-rock, while others traverse the strike more or less at right angles. In mountain tracts lodes not infrequently run parallel to the general axis of elevation. Hence, if the date of the elevation be known, the age of the faults

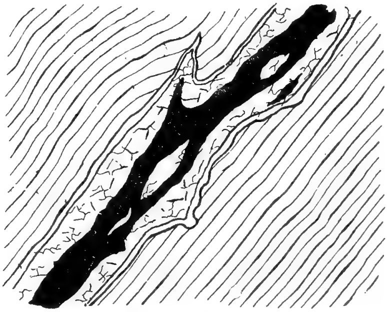


FIG. 91.—COINCIDENT LODE. (After R. Beck.)

and fissures is at once determined. As crustal movements have often affected the same area at different periods, and not infrequently in different directions, new systems of divergent and intersecting folds and fissures have successively been produced, the relative age of which can usually be ascertained by observing the behaviour of one system to another.

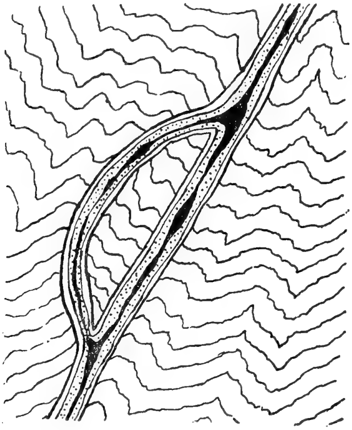


FIG. 92.—LODE DIVIDING AND RE-UNITING.

Branching and Intersection of Lodes.—Lodes not infrequently divide into two or more branches, which, after pursuing separate courses for longer or shorter distances, again come together (see Fig. 92). Occasionally, also, two lodes may gradually converge until they meet, and then, after running side by side for some little way, may again diverge (see Fig. 93); or, instead of diverging, one may intersect the other without displacing or shifting it, and subsequently resume its original direction

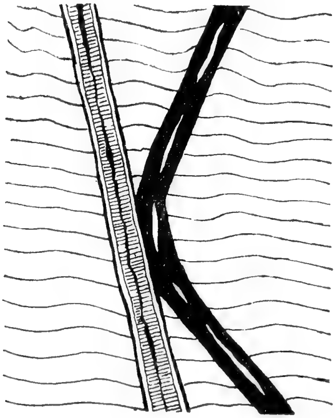


FIG. 93.—LODES CONVERGING AND DIVERGING.

(see Fig. 94). In such a case the fissure occupied by the intersecting and therefore younger vein is obviously a simple rent and not a true fault. Occasionally, two veins meet at approximately right angles, the younger similarly intersecting the older without displacing it (see Fig. 95). Very

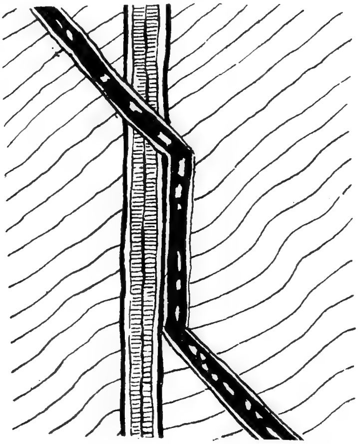


FIG. 94.—LODES CONVERGING AND INTERSECTING.

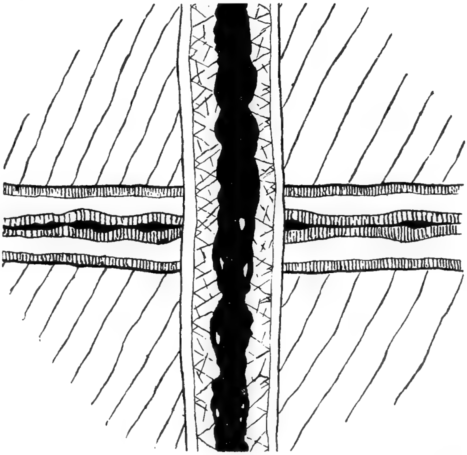


FIG. 95.—LODES INTERSECTING AT RIGHT ANGLES WITHOUT DISPLACEMENT. (Plan).

rarely two fissures intersecting at right angles have received their mineral contents at the same time (see Fig. 96).

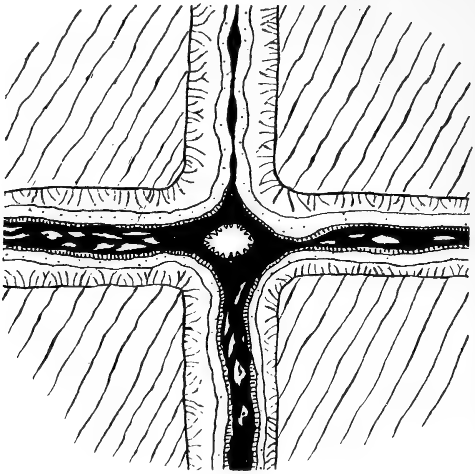


FIG. 96.—CONTEMPORANEOUS CROSS-VEINS. (Plan).

Heaving of Lodes.—When the intersecting lode occupies a fissure of displacement or true fault, it invariably shifts or heaves the lode it traverses (see Fig. 97). If the fault be normal, then the older lode is shifted in the direction of the downthrow; in the case of a reversed fault the older lode will, of course, be heaved in the opposite direction.

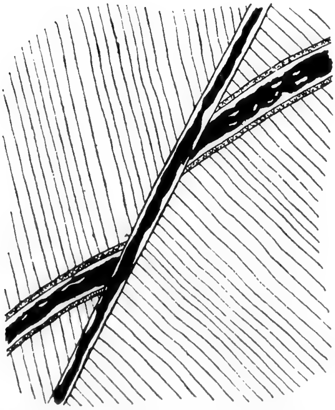


FIG. 97.—HEAVING OF ONE VEIN BY ANOTHER.

Contents of Fissure Veins.—These are known as *veinstone*, *veinstuff*, *matrix*, or *gangue*, and consist largely of crystallised minerals, such as quartz, calcite, and other carbonates (dolomite, magnesite, etc.), barytes, and fluor-spar. Fragments of the "country" (*i.e.* the rocks traversed by a lode) frequently appear, and often constitute the larger portion of the veinstuff. The fragments are of all shapes—angular, subangular, or rounded—and some of them may show smoothed and striated surfaces. They vary also in size, from large blocks down to finely comminuted particles. The ores are irregularly distributed through the veinstone as grains, crystals, patches or bunches, laminæ, threads and strings, often crossing and recrossing. Sometimes they assume the form of vertical or steeply inclined columnar or chimney-like aggregates, surrounded on all sides by lean or barren veinstuff. Such rudely columnar ore-bodies are known as *shoots*. Or they may appear in the form of more or less regular plates and tabular sheets, disposed in parallel positions with similar plates of veinstone; or, again, they may occur as massive aggregates occupying the whole fissure to the exclusion of any veinstuff. On the other hand, ore may be entirely wanting in some parts of a lode, the fissure being either filled with veinstone and rock-rubble only, or closed by the apposition of its walls.

Structure of Fissure Veins.—(*a*) MASSIVE STRUCTURE. When a fissure is entirely filled with ore, or with crystallised or cryptocrystalline mineral matter containing ore disseminated through it, the structure is said to be massive (see Fig. 87, p. 239). Galena (lead-ore), for example, is often met with completely filling fissures—crystallised veinstone being either entirely absent or occurring only as small inclusions in the ore, or as a meagre interrupted layer lining the walls. Auriferous quartz-veins are an example of the same structure—the ore in this case being included in the quartz which wholly fills the fissure.

(*b*) PLATY, LAMELLATED, OR BANDED STRUCTURE.—In this structure the ore and the veinstone are disposed in more or less sharply defined sheets or layers parallel to the walls of the fissures (Plate L. 1). This is the commonest kind of structure met with in lodes. The sheets are of very variable thickness, and may be few in number, in which case some or all may be relatively thick; or they may be numerous and all extremely thin—mere laminæ of irregularly alternating ore and veinstuff. Now and again, however, they are arranged symmetrically in pairs. The opposite walls may each be lined, for example, with a layer of quartz or other veinstone; to this may succeed two bands of ore, one on either side—and such duplication may be repeated again and again, until the fissure is completely filled (Fig. 98). Such a banded lode is said to be *symmetrical.* The crystallised minerals are often prismatic—their longer axes being perpendicular to the walls and their pyramidal terminations directed towards the centre of the vein. A section across such a sheet has suggested to mining folk its resemblance to a comb, and thus we have the term *comby lode* applied to symmetrical fissure-veins. Frequently, the fissures are not completely filled—medial cavities of less or greater extent being left. These are termed *vughs* or *druses*, and are usually lined with crystallised minerals.

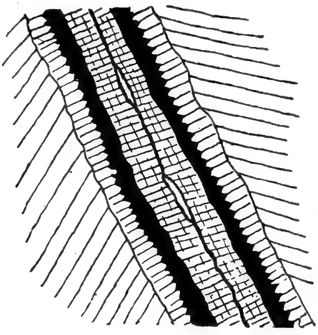


FIG. 98.—LAMELLATED LODE WITH DRUSES.

(*c*) BRECCIATED STRUCTURE.—Some lodes are largely brecciated—abundant fragments of mineral plates or lamellæ, together with pieces of the country-rock, being scattered through amorphous or irregularly crystallised veinstuff. This structure shows that the fissure occupied by a banded lode has been subsequently reopened—the crustal movement resulting in the fracturing and shattering of the platy layers of the original lode and the introduction into the reopened fissure of fragments of the country-rock. Later on, this jumbled mass has been permeated by metalliferous and mineral solutions, which have bound the débris together (see Fig. 99 and Plate L. 2). Now and again these subsequently

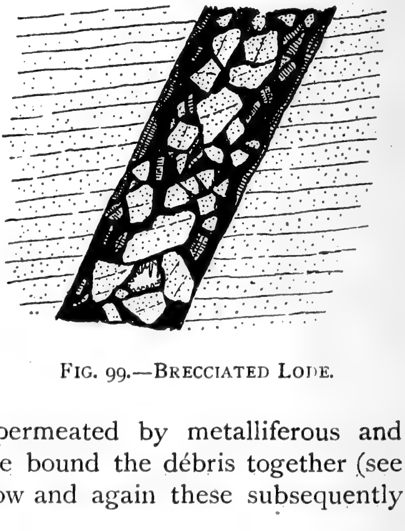
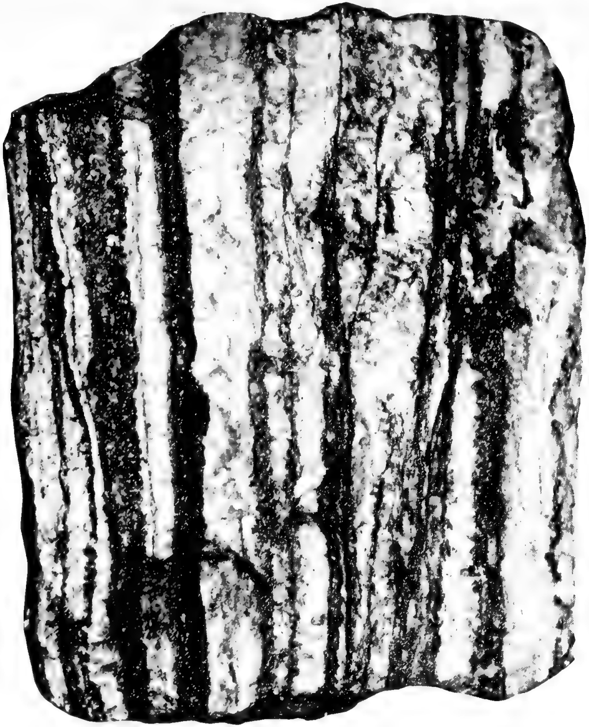
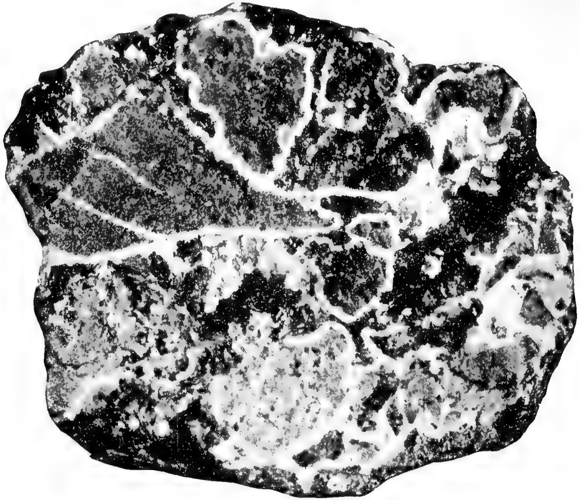


FIG. 99.—BRECCIATED LODE.

PLATE L.



1. PORTION OF A LAMELLATED LODE OR METALLIFEROUS VEIN. The dark bands are ore, the white bands "veinstone." Two-thirds natural size.



2. PORTION OF BRECCIATED LODE. The white portions are "veinstone"; the irregular-shaped areas surrounded by thin white bands (veinstone) are fragments of "country-rock." The intermediate dark areas are mostly ore. Nearly natural size.

[*To face page* 246.

introduced ores and crystalline minerals, in place of being diffused through the débris, are found encrusting the embedded pieces of country-rock and fragments of older veinstone with successive layers, forming what are termed *ring ores* or *cockade ores* (Cocardenerze).

In some reopened and refilled veins the products of the first infilling have not been entirely broken up—the fissure has simply been widened and a new comby lode has been formed outside of and parallel to the original symmetrical lode. This reopening and refilling process has in certain cases been repeated several times, the lode consisting of a succession of duplicate sheets, each two or more bands representing a separate infilling (see Fig. 100). Many other structures may be observed in reopened fissure-veins. Occasionally, the new cavities are crowded entirely with rock-débris, which may or may not be ore-bearing. Now and again, however, the interstices and wider spaces between some of the larger blocks detached from the walls have not been completely filled with new mineral matter. In such cavities (or *vughs*) finely crystallised minerals and stalactitic formations frequently appear.

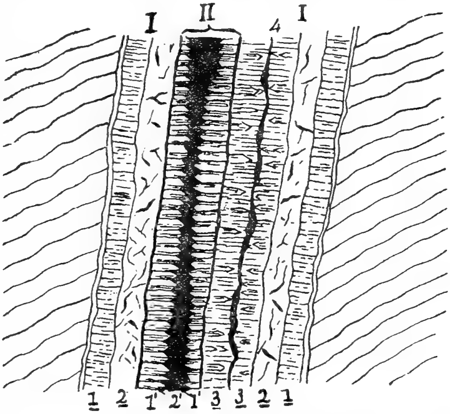


FIG. 100.—REOPENING AND REFILLING OF VEINS.
I—1, 2, I—1, 2, 3, 4, first infilling; II—1′, 1′, 2′, second infilling.

Outcrop of Lodes.—The line along which a lode comes to the surface is variously termed *outcrop*, *outgoing*, or *back*. When a lode consists of more durable ingredients than the rock it traverses, as is frequently the case with quartzose lodes, it projects at the surface, and forms what miners term a *reef*. On the other hand, should a lode be less durable than the country-rock, its outcrop is revealed by a trench-like depression. Lodes, however, are often concealed underneath superficial deposits. Some, again, do not reach the surface—either owing to the dying-out of the fissures, or to the subsequent accumulation above the country-rock of later sedimentary or igneous formations. It is probable, indeed, that lodes exist in many unsuspected places—more particularly in regions where considerable unconformities occur. They are met with traversing rocks of all ages—Palæozoic, Mesozoic, and Cainozoic alike; but, as might have been expected, are of more frequent occurrence in Palæozoic than in Mesozoic, and in Mesozoic than in Cainozoic rocks. They are most commonly associated with metamorphic rocks and eruptive masses, although this is by no means invariably the case.

Gossans.—A lode at its outcrop is usually more or less weathered, and of a rusty brown, red, or yellowish colour from the frequent presence of ferruginous matter. Such weathered backs are termed *Gossans.* The thickness or depth of gossans is quite indeterminate. Sometimes they extend to a depth of many fathoms, but usually they do not go much below the water-level of a district. Native metals (gold, silver, copper), carbonates, sulphates, and phosphates of metals, and other metalliferous compounds often occur in relatively large proportion in gossans. All these are the products of the decomposition of the ores of the original or unaltered lode. As the lode is followed to greater depths, native metals and oxidised ores gradually disappear, and are succeeded by sulphides or other compounds devoid of oxygen. As the present surface at which lodes crop out must be far below that which existed at the time of their formation, it will be readily understood why metals such as gold and silver should often occur in relatively large proportion in the gossans of auriferous and argentiferous lodes. The outcrop of a vein is necessarily lowered with the general lowering of the land-surface by denudation. The chemical action of percolating water affects the metalliferous contents of the lode, which ere long become oxidised, and may even be reduced to the state of native metals. These last, owing to their superior weight and insolubility, are not washed away with the lighter and more soluble constituents, and thus tend to become concentrated in the gossan. This is the reason why the gossanous parts of auriferous and argentiferous lodes are usually richer than the underlying, unweathered portions. The richness of a gossan, therefore, is apt to deceive the unwary as to the value of the subjacent deposit—rich gossans having sometimes been found capping lodes which were too poor to work. When a gossan yields valuable metals or ores, it certainly indicates the presence of these in the lode below; but whether the latter is rich enough to be advantageously worked cannot be determined until the undecomposed material below the gossan has been carefully examined. The effect of percolating water can frequently be traced to a considerable depth below the "iron-hat"—or true gossan—the general result being a concentration of secondary products, consisting partly of oxides and partly of sulphides. This *secondary enrichment* of a lode sometimes extends to a depth of 600 feet or even 750 feet from the surface.

Association of Ores in Lodes.—The minerals in lodes often show paragenetic relations—that is to say, certain minerals are frequently found associated. For example, manganese- and iron-ores often occur together, and the same is true of galena (PbS) and zinc-blende (ZnS), of cobalt- and bismuth-ores, and of cobalt- and nickel-ores. In like manner the copper-sulphides (bornite and chalcopyrite) not infrequently are accompanied by iron-pyrite. Again, when bismuth glance (Bi_2S_3) is present, chalcopyrite is seldom or never absent. Similarly, pyrrhotite and chalcopyrite are constant associates. Once more, it is most usual to find fluor-spar, topaz, molybdenite (MoS_2), wolframite [$(Fe,Mn)WO_4$], and cassiterite (SnO_2) occurring together in the same ore-formation.

Succession of Mineral Deposits in Fissures, etc.—It is not hard to understand why ore-deposits should often seem to have preferred one rock to another. It is obvious, for example, that relatively hard, porous, and highly fissured rocks would be more readily traversed by solutions, than soft impervious masses, in which joints and faults are apt to be close, and even approximately water-tight. Again, some rocks, particularly limestone, are more or less readily dissolved by acidulated water, and thus, in time, yield ample space for the deposition of such ores as galena and hæmatite. Very often, however, the large ore-bodies occurring in limestone, are simply cases of metasomatic replacement. The precipitation of ores, indeed, would seem to have been frequently induced by chemical reaction between metalliferous solutions and the country-rock. If the latter contained carbonaceous matter, for example, this would bring about the deposition of sulphides from solutions of metallic sulphates. Precipitation might also be expected to occur in places where subterranean currents, differing in temperature and in the nature of their solutions, came together. Further, in the case of ascending currents it is obvious that gradually diminishing heat and pressure must have played a dominant rôle in determining the deposition of substances held in solution.

But when we study the succession of minerals in banded lodes, it must be admitted that no general law governing that succession can be recognised. We can only conjecture that the chemical composition of the solutions circulating through the fissures may have varied from time to time. Sometimes it would appear as if successive deposition had been determined by the relative solubility of the minerals. Frequently, for example, quartz lines the walls of a lode, and is overlaid by calcite. Again, it is highly probable that the earlier deposits of ore in a lode may not infrequently have played the part of precipitants to later introductions. Thus copper solutions might be reduced by iron-pyrite, the reaction giving rise to the formation of chalcopyrite. It is well known also that the iron-pyrite of auriferous quartz-veins frequently contains gold. In short, it seems not at all unlikely that many of the common associations of ores referred to above may be the result of one ore having acted as the precipitant of another.

Even in one and the same lode the mineral succession is often repeated several times, showing that at intervals similar conditions have recurred again and again. As the same succession of minerals may appear in lodes filled at widely separated geological periods, while lodes of the same age may differ greatly as regards their contents and the order of mineral succession, it is obvious that the nature and arrangement of the ores and other minerals in lodes can tell us nothing as regards the geological age of the deposits.

So far as observations have yet gone, it would seem that differences of depth have had considerable influence on the deposition of minerals in lodes. In many regions where lodes are worked, the present surface of the ground must be several thousand feet or even yards below the surface that existed when those fissure-veins were filled. In other cases we have no reason to believe that any such excessive denudation has taken place. We have the opportunity, therefore, of studying ore-deposits which have been formed at very great depths, and comparing them with others of much less deep-seated origin. Professor De Launay has cited quicksilver-formations as an example of the latter—since they appear to be restricted chiefly to rocks of relatively recent geological age which have been traversed by eruptive masses. According to De Launay, they do not occur in regions of older rocks or associated with eruptives of great age, simply on account of the extreme denudation which those regions have experienced. The upper parts of the older lodes, which may have carried quicksilver, have long since been removed, along with the country-rock traversed by them, so that it is only the pyritic or deep-seated ore-formations which are now encountered in the lodes of profoundly denuded regions. Again, Professor Vogt has pointed out some remarkable differences between gold-, silver-, and lead-bearing veins of relatively recent age, such as those of Comstock, Potosi, Hungary, etc., and the much older lead-silver veins of Norway, Bohemia, the Erzgebirge, etc. In both cases the lodes are closely associated with eruptive rocks, and the country-rock has undergone much alteration, so that the conditions attending the deposition of the ores and veinstones in all the regions referred to appear to have been similar. The differences referred to by Professor Vogt have reference not only to the contents of the lodes, but to the changes which have been superinduced on the country-rocks; and these differences, according to him, indicate that the older have been formed at a greater depth than the younger veins. From his point of view, therefore, the latter, if they were followed downwards, would gradually assume the character of the former. Whether such would prove to be the case is, of course, conjectural, but Vogt's hypothesis is to some extent supported by the phenomena revealed in certain deep mines. In the Cornish mines, for example, after passing down through their gossans the lodes were found to carry copper-ore with some tin-stone; at a still greater depth, a zone of mixed tin-stone and copper-ore was encountered, and under that tin-stone almost exclusively. So, again, in lodes carrying silver-lead-zinc ores it has frequently been observed that the proportion of zinc-blende increases with the depth. It would seem, also, that in many manganese-iron formations the proportion of iron similarly increases downwards. But much additional observation and study will be required before the laws governing the genesis and deposition of ore-formations can be clearly comprehended.

Walls of Lodes.—Occasionally the walls of lodes are more or less slickensided—owing, doubtless, to the one being ground against the other. [The smoothed and slickensided stones which not infrequently occur in the contents of lodes have already been mentioned. These are probably in some cases fragments detached from the walls after the latter had been smoothed; in other cases, they may have been slickensided *in situ*, the blocks and stones being pressed and rubbed against each other during movements of the country-rock.] Frequently the walls of a lode are more or less decomposed, the width of decomposed rock being very variable. Sometimes it may hardly exceed an inch or two, while in other cases the rock may be rotted for many feet or yards away from a lode. On the other hand, the walls have often been rendered excessively hard by the infiltration of silica. Many lodes as they are followed downwards show only one wall, usually the footwall. In place of a definite hanging-wall, we may have a considerable breadth of much shattered and jumbled rock, the fissures between the separate blocks and fragments being sealed-up with veinstone and ore (see Fig. 88, p. 240). In other cases walls may become obliterated, as it were, by the gradual passage outwards of veinstuff and ore, which seem to merge insensibly into the country-rock. In yet other cases no definite walls can be traced, and a central fissure may or may not be seen. This is often the case with *impregnations*, to which reference will presently be made. As a rule, when the fissure occupied by a lode is a normal fault, one or both walls are well defined. The rocks on the downthrow side of such a fault are often highly shattered, while those on the upcast side are usually not much broken. When such a fault, therefore, is subsequently occupied by an ore-formation, it is the hanging-wall rather than the footwall that tends to be ill defined. When a lode shows no definite walls, the original fissure is more frequently a simple rent than a true fault.

The ores and veinstones of a lode frequently invade the country-rock not only as impregnations, but as sheets (*flats*) and subordinate veins. These may be looked upon as merely extensions of the lode. Sometimes they penetrate the country-rock along planes of bedding, of cleavage, or foliation; in other cases, they obviously follow the subordinate cracks and rents which so often accompany faults.

Stockworks.—Now and again a mass of rock which may consist of sedimentary, of igneous, or of schistose materials, may be very much jumbled or crushed, and traversed by an infinity of minute, reticulating joints and fissures. This, as already mentioned, is not infrequently the case with the country-rock traversed by some lodes. But highly fissured rock-masses are not necessarily connected with great lodes. Rocks of various kinds tend to be more or less abundantly jointed while they are becoming solidified. This is markedly the case with plutonic rocks which have consolidated from a state of igneous fusion. Fissures of contraction formed in this way are liable to be filled with subsequently introduced mineral matter. It has frequently happened, therefore, that fissured rock-masses have been permeated by ore-bearing solutions to such an extent that the rock can be mined in successive floors, forming what is known as a *Stockwork* (see Fig. 101). The infinitely numerous veins, veinlets, strings and threads of ore branch and interlace often in a most confused and irregular manner, although sometimes they tend to traverse the rock in certain more or less definite directions. The richness of a stockwork is frequently increased by the impregnation of the rock itself.

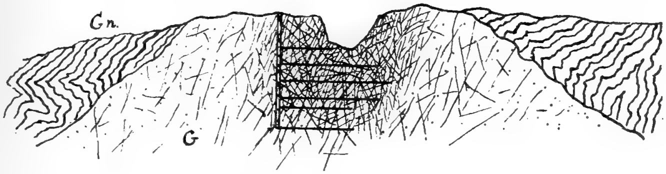


FIG. 101.—STOCKWORK.
gn, gneiss, etc.; *g*, granite.

General Remarks on Fissure-veins.—From what has been said in preceding paragraphs, it will be gathered that a lode may present many different features throughout its course. It may be massive in some places, banded and brecciated elsewhere. It may widen and contract irregularly, and may even pinch-out again and again. At the same time it may be accompanied by parallel veins or lodes, some of which may be independent, while others may be off-shoots or branches, which, after continuing their courses for longer or shorter distances, may again converge and rejoin the parent lode; or, instead of doing so, they may gradually thin out either simply or by subdividing into a complex of veinlets and threads. Both walls may be well defined throughout; or one, usually the hanging-wall, may be rendered indistinct, either owing to the multitudinous fissuring of the rock, or to the abundant dissemination of mineral matter through the pores and capillaries of the "country," or to the metasomatic replacement of the latter. Or dissemination and replacement together may succeed in obliterating both walls. On the other hand, many lodes are wonderfully regular, continuing between definite walls, showing much the same structure throughout, and varying but little in width or in the nature of their contents. Lastly, fissure-veins, instead of occurring as more or less well-defined lodes following some determinate direction, may form a close network of reticulating and intercrossing veinlets and threads, occupying all the cracks and crannies of a much divided and shattered rock-mass.

CHAPTER XVII

ORE-FORMATIONS—*continued*

Bedded Veins or Quasi-bedded Ore-Formations. Irregular Ore-Formations—Masses occupying Cavities; Metasomatic Replacement; Impregnations; Disseminations; Contact Ore-Formations. Origin of Ore-Formations — Magmatic Segregation Ores; Magmatic Extraction Ores; Secretionary Ores; Sedimentary Ores; Theories of Lateral Secretion and Ascension.

2. BEDDED VEINS OR QUASI-BEDDED ORE-FORMATIONS

WHEN sheets of ore occur apparently interbedded amongst more or less metamorphosed sedimentary rocks or schists, into which they send veins and threads, they may be termed bedded veins or quasi-bedded ore-formations. These formations are not to be confounded with the *flats* which are associated with "masses" (p. 259), and not infrequently also with lodes (p. 252), for they are not connected with true fissure-veins or lodes. Their origin is obscure. Not infrequently they seem to occupy planes of weakness or cavities, produced during the process of folding and metamorphism—for the rocks among which they occur usually dip at high angles and are more or less altered. The veinstone in some cases is commonly quartz which often carries gold and various metallic sulphides. While bedded veins of this kind are not infrequently of considerable width, and may simulate the persistence of true lodes, both as regards lateral and vertical extension, they are usually more or less lenticular and interrupted. A good example is furnished by the "saddle-reefs" of Bendigo Goldfield (Victoria, Australia) (see Fig. 102). The country-rock at this place consists of slaty-shales and altered sandstones, disposed in a series of steep anticlines and synclines. The abrupt plication of the rocks has caused lenticular spaces to occur between adjoining beds in the cores of the anticlinal and synclinal folds. These spaces subsequently filled with quartz form the so-called "saddle-reefs." Each reef is thickest along the middle line or axis of a fold, the anticlinal reefs tapering off downwards, and the synclinal reefs upwards. There would seem to be a succession of such reefs occurring one above another, at greater or less intervals, the anticlinal reefs being more frequent and better developed than those occurring in the synclinal cores. At Bendigo, narrow dykes of dolerite are associated with the reefs. The reefs carry native gold and auriferous sulphides in small grains and particles, as well as sharply angular fragments of the country-rock.

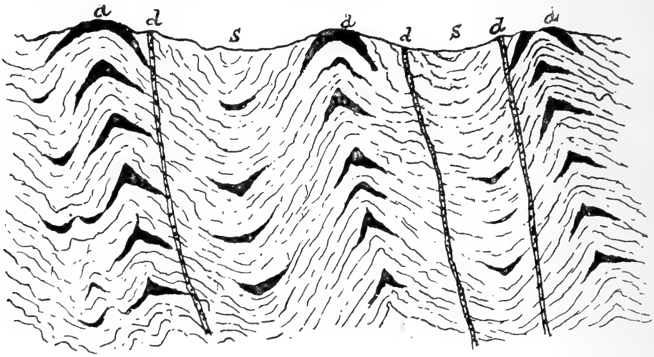


FIG. 102.—DIAGRAM-SECTION TO SHOW THE GENERAL STRUCTURE OF "SADDLE-REEFS."

a, a, anticlines; *s, s,* synclines; *d, d,* dykes.

[The famous Broken Hill silver lode of New South Wales is, according to Pittman, another example of a bedded "saddle-reef." Broken Hill itself is a low range composed of various schistose rocks, forming an anticline, the axis of which coincides with the crown of the range. The back of the great saddle-reef, before it was exploited, formed the crest of the range for a mile and a half, but it has now been nearly all quarried away, the open cut varying in width from twenty to one hundred feet. It was composed mainly of massive manganiferous limonite, yielding certain percentages of silver and lead. Throughout this mass many cavities (*vughs*) occurred, containing crystals of carbonate of lead (cerussite), chloride, iodide, and chloro-bromide of silver, and stalactites of psilomelane. Underneath this gossan or "iron-hat" a thick zone of so-called "oxidised ores" and native silver was encountered, the zone yielding variable but often very high percentages of the precious metal.

Further down the lode was found to consist of massive sulphide ore—an intimate mixture of argentiferous galena and zinc-blende, containing 5 to 36 ounces of silver and 2 or 3 pennyweights of gold per ton. The Broken Hill lode is the largest of the kind hitherto encountered. "In the widest part of the oxidised zone it contained payable ore for nearly three hundred feet in width, and at the present time (1900) the lode is being worked for a width of about four hundred and fifty feet (consisting of solid sulphide ore)."

If this great "reef" really occupies what was originally a cavity formed during the folding of the rocks—the crustal deformation could hardly have been deep-seated, otherwise the space ought to have been obliterated by the crushing-in of the compressed rock-masses. It is perhaps just conceivable that, if the folding was a very protracted process, ascending ore-bearing solutions may have been gradually introduced, deposition taking place *pari passu* with the formation of the cavity. It is doubtful, however, if the ore-formation in question is really of the nature of a "saddle-reef." It ought to be added that intrusions of granite and diorite traverse the schistose rocks with which the silver-lode is associated.]

It must not be supposed that the ore-formations here described as "bedded-veins" are always so sharply marked-off from the rocks amongst which they occur, as in the examples given. Often enough the ore-bed opens out, as it were, and so shades off gradually into overlying and underlying beds. In many cases, indeed, it is obvious that a so-called "bedded vein" or quasi-bedded ore-formation is merely a schistose rock which has been so highly impregnated with ore, that it can be advantageously mined.

It must be admitted that it is often very difficult to distinguish between such ore-bearing schists and those which have been described (see p. 234) under the head of syngenetic ore-formations. Probably not a few of the quasi-bedded ore-bodies associated with crystalline schistose rocks are largely of syngenetic origin—their original character having been more or less obscured by subsequent modifications brought about by epigenetic action. Amongst the quasi-bedded ores occurring in schists are both oxides and sulphides, but particularly the latter — such as zinc-blende, iron-pyrite, chalcopyrite, galena, etc. The precise origin of many of these ore-bodies, as already remarked, is obscure. In some cases they may be the result of metasomatic action, and thus replace pre-existing beds. That many of the ores, however, are true impregnations and disseminations cannot be doubted—not infrequently perhaps effected during the period of metamorphism, while others would seem to have been introduced at a later date.

3. Irregular Ore-Formations

1. **Masses.**— The ore-formations grouped under this head are met with chiefly in limestones. Sometimes they occupy underground cavities—the deserted courses of subterranean waters—which they partially or completely fill; in other cases the ore-formation would appear to be the result of metasomatic replacement—that is to say, the country-rock has been transformed into ore by the more or less complete chemical replacement of its original constituents.

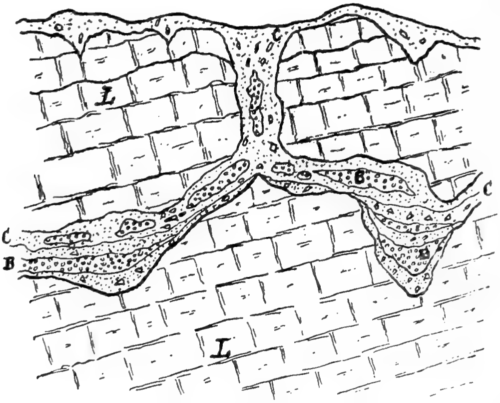


Fig. 103.—Diagram to show Mode of Occurrence of Bohnerz.
B, Bohnerz or oölitic limonite; C, cave-earth, etc.; L, limestone.

(*a*) *Masses occupying Cavities.*—Among the best examples of this type are the Bohnerz deposits which are so frequently met with in the Mesozoic limestones of middle Europe. (Fig. 103). Bohnerz is an oölitic or pisolitic limonite—the spherical grains of which vary in size from turnip seeds to hazelnuts, and often show a concentric radiated structure. The ore is usually charged with many impurities, such as clay, sand, etc., and not infrequently contains fossil organic remains of Tertiary age—such as mammalian teeth and bones, together with plants. In most cases the formation would seem to be a deposit from springs; but occasionally the ironstone occurs in the form of water-rolled fragments, associated with other sedimentary materials. It may be inferred, therefore, that these have probably been derived from some pre-existing formation, which has been broken up at the surface and the débris introduced underground by the mechanical action of water.

Irregularly shaped masses of hæmatite occurring in limestone may sometimes have been deposited in caverns and underground water-courses, and a similar origin has been assigned to many analogous masses of galena and zinc-blende enclosed in the limestones of various regions. The joints and even the bedding-planes of a limestone, in the vicinity of a "mass," are frequently charged with the same ore, forming what are known as *flats*, *gash-veins*, *pockets*, *bunches*, *pipes*, *nests*, etc. (Fig. 104). It is very doubtful, however, whether the ore-masses in question occupy pre-existing cavities. Probably most of them should be included in the next group (*b*).

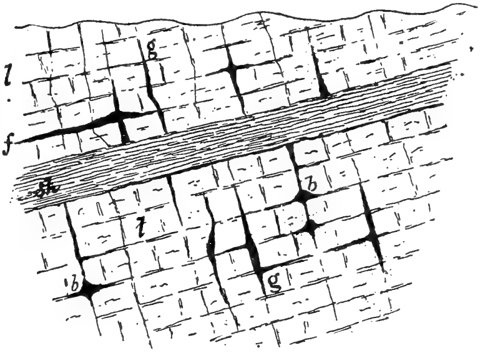


FIG. 104.—VEINS IN LIMESTONE.
l, limestone; *sh*, shales; *b*, *b*, bunches; *f*, *flat*; *g*, *g*, gash-veins.

(*b*) *Masses due to Metasomatic Replacement.*—This remarkable change is well illustrated by the transformations undergone by limestone, which is sometimes replaced by ores of iron, lead, zinc, or silver. Some of the masses of red hæmatite met with in the Carboniferous limestone of Cumberland, are clearly cases of metasomatic replacement, and possibly, as already suggested, the same is true of them all. The accompanying section (see Fig. 105), by Mr J. D. Kendall, tells its own tale. Here the replacement of the limestone is rendered conspicuous by the shaly partings and layers which traverse the hæmatite, and are obviously continuous with the similar layers and partings in the limestone at b^1. The limestone has been transformed into ore, while the argillaceous shales (with which no chemical reaction could take place) remain unchanged. There is, moreover, a gradual transition from the hæmatite into the limestone—the one is not sharply marked off from the other. It may be added that the characteristic fossils of the limestone are often partly or completely changed into iron-ore. Similar phenomena occur in limestones and dolomites of various ages elsewhere. Thus, in Carinthia, Triassic calcareous rocks are metasomatically replaced by ores of zinc, while in Nevada, Utah, and other regions in North America certain limestones have been extensively converted into silver-ores.

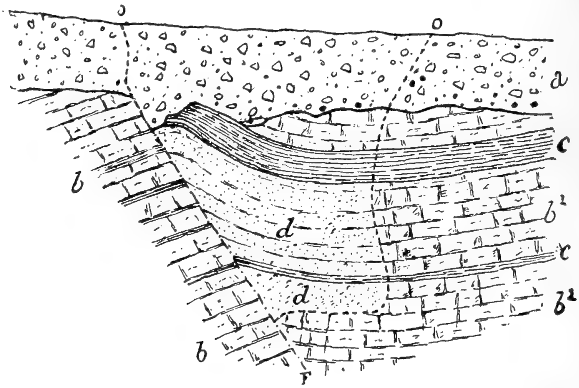


Fig. 105.—Metasomatic Replacement of Limestone by Hæmatite.
a, boulder-clay; *b*, limestone; b^1, siliceous; *c*, *c*, shales; *F*, fault; *d*, hæmatite replacing limestone; *o*, *o*, sides of the open cut. (After J. D. Kendall.)

2. **Impregnations.**—Reference has already been made to the impregnations which so frequently affect the walls of certain lodes and the rocks of a Stockwork. In cases of this kind the ores occur partly as disseminations (*i.e.* they occupy pre-existing pores and interstices), and partly as metasomatic replacements. For example, in a granite impregnated with tin-ore we frequently find the ore not only occupying minute

fissures in the rock, but here and there replacing the felspar, the form of which it retains. It is this constant passage of one type or form of epigenetic ore-formation into another that makes it impossible to separate them into well-defined or natural groups.

3. **Disseminations.**—Ores are sometimes disseminated through a rock in such a way as to show that they are not original constitutents of the rock, but have been subsequently introduced; for they occupy its minute pores, interstices, capillaries, and larger cavities. A good example of this kind of ore-formation is supplied by the copper-bearing sandstones and conglomerate which were formerly worked at Alderley Edge and Mottram St Andrews, near Macclesfield. Green hydrated copper carbonate (malachite) and the blue variety (azurite) are disseminated through the cementing material of the rocks, the constituent grains and pebbles being in this way coated with ore. Small quantities of ores of lead, manganese, iron, and cobalt occur in the same sandstones. The most notable examples, however, of such disseminations are the auriferous conglomerates of the Rand in Transvaal, S. Africa. The strata of sandstone in which the gold-bearing conglomerates occur at Witwatersrand, dip at a high angle (60° to 80°), but the inclination decreases as the beds are followed downwards. Gold occurs chiefly in the siliceous cementing material of the conglomerates, and is highly crystalline, appearing with sharp edges under the microscope. In this respect it differs from the gold of placers, much of which shows no trace of crystalline form. Associated with it are many secondary minerals, such as pyrite, marcasite, chlorite, talc, sericite, etc. The strata contain no fossils, and were probably accumulated in a lake. Subsequently the whole series of deposits were subjected to crustal movement, being tilted, compressed, fractured, and faulted, and then or at a later period were traversed by dyke-like intrusions of various igneous rocks (see Fig. 106). Concurrently with the crustal disturbance or with the igneous intrusions, siliceous and metalliferous solutions permeated the strata, making their way more readily through the conglomerates than the close-grained sandstones. Hence it is in the former that gold and crystallised minerals occur most abundantly. It is worthy of note, however,

that gold is confined to particular beds of conglomerate—other layers of the same kind of rock containing little or none. Possibly this may be explained by the presence of reducing agents in the one case and their absence in the other. According to Messrs Hatch and Corstorphine it is difficult to say what this reducing agent was. They point to the frequent association of gold with pyrite as suggesting that the latter had something to do with the precipitation; and they suspect that the carbonaceous matter—plentifully present in some richly auriferous portions of a conglomerate—may have played a greater rôle as a reducing agent than is commonly supposed.

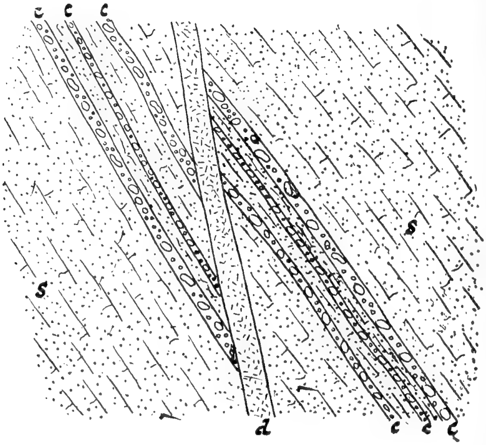


FIG. 106.—REVERSED FAULT IN THE GOLD-BEARING ROCKS AT JOHANNESBURG. (After Schmeisser.)

s, *s*, sandstones, etc.; *c*, *c*, *c*, beds of gold-bearing conglomerate (so-called "reefs"); *d*, dyke lying in fault.

Yet another example of disseminations may be given. At Keeweenaw Point, Lake Superior, occur certain much decomposed igneous rocks (melaphyres) with interbedded conglomerates. Native copper is found both in the conglomerates and the igneous rocks, which are old lavas, the pebbles of the former being often encrusted with it, while the amygdaloidal cavities of the latter are frequently lined and occasionally completely filled with the same metal. Copper occurs also in the joints of the rocks and the fault-fissures traversing the strata, so that at Keeweenaw Point we meet with a union of at least two kinds of ore-formation—disseminations and true fissure veins—both of which have doubtless had the same origin and were formed at the same time. The copper is often enclosed in, or itself encloses, zeolites, thus clearly showing it has been introduced as an aqueous solution. The whole series of rocks, after having been fissured and faulted, has been acted upon by hot and cold percolating waters, which have produced much alteration, probably leaching out the copper from the igneous rocks, and depositing it where it is now found.

The famous copper-slate of Mansfeld, in Thuringia, which has been worked for several centuries, belongs to a class of ore-formations which some have considered to be a kind of connecting link between epigenetic and syngenetic accumulations. The Kupferschiefer (copper-slate) is one of the subdivisions of the Permian system of Germany. The succession of deposits in Thuringia being as follows :—

5. Bunter (sandstone, etc.).
4. Zechstein (dolomite with rock-salt and gypsum).
3. Kupferschiefer (copper-slate or shale).
2. Weissliegendes (thin white sandstone).
1. Rothliegendes (red sandstone and conglomerate).

The ores occur chiefly in the Kupferschiefer and mostly in its lower portion, being disseminated usually in fine grains or occurring in thin layers and nests. So abundant is this fine dust-like dissemination that the rock when broken across gives a metallic reflection in sunlight. The most abundant ores are sulphides of copper, but associated with these occur ores of silver, zinc, lead, iron, nickel, cobalt, etc., mostly as sulphides or compounds devoid of oxygen. The copper-slate is black and bituminous, not more than two feet thick, and sometimes so hard that it rings under the hammer. It is often crowded with fish-remains, and with relics of conifers, such as twigs, cones, and leaves, the fossils being often encrusted with or replaced by ore. The presence of a brachiopod (*Lingula*) is suggestive of the marine origin of the shales. The whole character of the strata, however, leads to the belief that deposition took place in an inland sea or salt lake. The origin of the ores has been much discussed, some holding that they are syngenetic, or, in other words, chemical precipitates. Those who maintain this view are of opinion that, during the formation of the shale-beds the water became occasionally habitable and swarmed with fish, which later on were poisoned by an abundant influx of water charged with salts of copper. Certainly the fossil fish of the copper-slate often occur in bent and contorted attitudes, as if they had been suddenly killed. Similar appearances, however, are met with in deposits which contain no ores. In the Old Red Sandstone of Dura Den, for example, whole surfaces of certain beds were covered with ganoid fishes, lying in all directions, often in convulsed attitudes. The same phenomena are encountered in the famous lithographic limestone of Solenhofen, in the Tertiary deposits of Monte Bolca, and even in the marl-slate of England, which is on the same geological horizon as the copper-slate of Mansfeld, but which, unlike the latter, contains no copper-ore. The sudden descent to the sea of a large volume of fresh water sometimes results in the wholesale destruction of fishes. Thus, in January 1857, an immense body of fresh water, descending by subterranean courses, was suddenly discharged upon the sea-floor off the coast of Florida. So great was this discharge that the saltness of the sea was sensibly diminished, and myriads of dead fish floated on the surface and were strewn along the shore. Again, earthquake shocks have sometimes been equally destructive. During the Indian Earthquake of 1897, for example, fishes were killed in myriads as by the explosion of a dynamite cartridge, and for days afterwards the river Sumesari was choked with their dead bodies. That similar results must have attended earthquake shocks in earlier ages cannot be doubted. As the sudden destruction and entombment in mud of large numbers of fish may be due either to sudden freshening of salt water or to earthquake shock, it is obvious that the abundant fish remains of the Mansfeld copper-slate cannot be cited in support of the view that they were poisoned by metallic solutions. It would seem more probable, therefore, that the ores by which they are encrusted are really epigenetic, or subsequent introductions. Further, it must be noted that the ore-formations in question are not confined to the bituminous slate, but are met with also in numerous fissures which pass upwards into the overlying Zechstein ; and it has been observed that the percentage of ore contained in the copper-slate itself increases as it approaches those fissures. It is remarkable that the Permian system, all the world over, is apt to show impregnations of copper-ore. Towards the close of that period crustal movements seem to have affected wide areas, while volcanic action was displayed in many regions. Possibly, therefore, it was during this period of subterranean activity that the strata were traversed by copper-bearing solutions ascending from below.

4. Contact Ore-Formations

Under this head are included sheets, irregular masses, ramifying veins and threads, etc., occurring in rocks usually at or near their junction with plutonic masses. These ore-formations (Fig. 107) include iron oxides and sulphides, and frequently also ores of copper, lead, zinc, tin, arsenic, antimony, mercury, etc. ; and, in some cases, gold and silver. They may occur at or very close to the junction-line—particularly when the rocks surrounding the igneous mass are much broken and jumbled ; or they may be met with at the surface for a mile or more away from an igneous batholith, but seem never to stray beyond the zone of altered and metamorphosed country-rock which surrounds it. They may occur in any kind of rock, and are frequently accompanied by the "contact minerals" referred to in a previous chapter (p. 217). Good examples are supplied by the cassiterite-veins which occur in genetic connection with batholiths of acid igneous rock, and the apatite-veins which are in like manner associated with masses of gabbro. The contents of these veins, as we have seen, appear to have been extracted from the still liquid or not yet fully congealed igneous masses and carried into the surrounding rocks. They are, in short, among the phenomena of contact metamorphism. According to Professor Vogt, who has made such phenomena a special study, many other ore-formations met with in the vicinity of eruptive masses are of the same origin. As examples, he refers to the pyritic deposits occurring at Sulitelma and other places in Norway, at Tharsis, San Domingo and elsewhere in Spain, at Rammelsberg in the Harz, and Schmöllnitz in Hungary. In all these cases the formation of the ore-deposits is ascribed to pneumatolytic processes, following eruptive intrusions. Vogt further draws attention to the fact that the younger gold and silver veins (such as those occurring along the Carpathians, and at many places in Colorado, Utah, Nevada, California, Mexico, Peru, Bolivia, New Zealand, Japan) are in like manner closely associated with recent eruptions of igneous

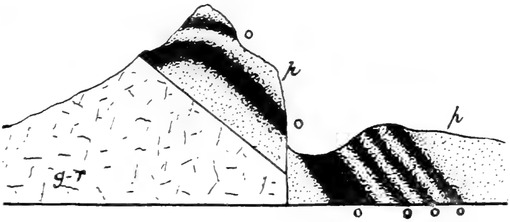


FIG. 107.—SECTION. CONTACT ORE-FORMATION OF GOROBLAGODAT (URAL MOUNTAINS). (After T. Tschernyscheff.*)
g-r, garnet-rock; *p*, orthoclase-porphyry; *o*, magnetic iron-ore.

---

* Until quite recently the iron-ore of Goroblagodat was considered to be an example of magmatic segregation, which is certainly suggested by Tschernyscheff's section. It is now, however, believed to be of epigenetic origin.

rock of various kinds. In each district where they occur they belong to the latest or one of the latest epochs of volcanic activity for that district. Hot springs, solfataras, etc., are frequently found near them, and even when these are absent the surrounding rocks are always more or less altered, as if they had been subjected to the action of heated water and vapours. The same authority would ascribe a similar origin to the older lead-silver veins of the Erzgebirge, the Harz, Kongsberg (Norway), Przibram (Bohemia), etc., and the old gold-quartz "Mother Lode" in California.

The ore-formations of Sarawak have been recently shown by J. Somerville Geikie to be true contact-formations. They include ores of iron, antimony, arsenic, zinc, lead, mercury, etc., and native gold and arsenic. The region is occupied chiefly by Mesozoic limestone and shales, which are often highly shattered and brecciated and saturated with silica. Numerous dykes and sills of quartz-porphyry traverse these rocks, and are supposed to proceed from a concealed batholith of granite. Indeed, only a few miles away from the mines granite comes to the surface to form considerable hills. The ores occur not in the form of true lodes but mostly as impregnations and disseminations in the shales, and as irregular bodies in the limestone. Now and again the dykes yield a small percentage of gold.

Origin of Ore-Formations.—Here we refer mainly to epigenetic formations—the origin of syngenetic ore-formations has already been sufficiently discussed. We have learned that native metals and ores of various kinds occur as original constituents of crystalline igneous rocks—the ores being sometimes so abundantly developed that they can be profitably worked. From the researches of Sandberger and others, moreover, we know that minute quantities of many of the heavy metals have been detected in such minerals as olivine, augite, hornblende, and mica. Olivine, for example, has yielded iron, nickel, copper, and cobalt; in augite have been detected iron, copper, and cobalt, and less frequently, nickel, lead, tin, and zinc, while antimony and arsenic are occasionally present; from hornblende have been obtained copper, arsenic, and cobalt, and not infrequently lead, antimony, tin, zinc, and bismuth; lastly, in the micas (which are often specially rich in the heavy metals), have been recognised tin, arsenic, copper, bismuth, uranium, lead, zinc, silver, cobalt, and nickel. Doubtless, the proportion of metal present in any individual mineral is extremely minute, but the sum of metal contained in this way by the several constituents of a rock-mass must really be very considerable. From the phenomena connected with contact ore-formations there seems no reason to doubt that a molten magma is not infrequently rich in metallic materials, and that solutions of metal have proceeded from many batholiths while these were solidifying and cooling. We seem, therefore, justified in concluding that igneous rocks are the chief, if not the only, sources from which the metals of most epigenetic ore-formations have *originally* been derived.

The ore-formations due to pneumatolytic action may be looked upon as connecting links between the truly syngenetic ores of eruptive rocks on the one hand, and the typical epigenetic ore-formations of lodes on the other. It is obvious that the process described as magmatic extraction is closely related to that of magmatic segregation. In the case of the latter the ore has separated out at the time of the eruption and consolidation of the molten magma. They are, in short, original constituents of the rocks in which they occur. Contact ore-formations are, no doubt, also of igneous derivation, for they consist of materials which have been extracted from a molten magma and carried into the country-rock by superheated vapours. They are thus epigenetic—*i.e.* of later date than the rocks which contain them. Even in cases where such magmatic-extraction ores penetrate the igneous rocks themselves as veins and impregnations, they may be yet described as epigenetic. For, in such cases, their formation must have been somewhat later than the consolidation of the rock they penetrate. It is quite possible, indeed, that they may have been derived from some still molten or imperfectly solidified portion of the igneous mass. While, therefore, such ore-formations probably owe their origin to solfataric or after-action, and may thus be said to belong to the same period of plutonic action as the igneous rock in which they appear, yet it is obvious that they must be of somewhat later formation, and are, therefore, properly included in the epigenetic class.

Concerning the origin of other epigenetic ore-formations, many different and often conflicting views have been held. They are all doubtless *secondary* formations, derived in the first place either from igneous rocks or from veins, etc., of pneumatolytic origin. The process whereby epigenetic ores in general have come into existence might be shortly defined as a process of concentration. By mechanical and chemical operations, igneous rocks have been broken up and the resultant products have gone to form sedimentary or aqueous deposits of one kind and another. These last have in their turn been subjected to similar changes —and new accumulations have been built up out of their ruins. At the surface of the earth it is the mechanical deposits—gravel, sand, and mud—which are most conspicuous, but immense quantities of materials are also carried in solution, some portion of which, under favourable conditions, may be observed forming here and there as chemical precipitates ; but the great body of dissolved mineral matter finds its way out to sea. The less soluble metals and metallic compounds derived from the disintegration of pre-existing rocks become concentrated in the mechanical and chemical sediments now in process of formation at the surface. This may be illustrated by the disintegration of a basic rock, such as basalt. By the various epigene agents of change, the ingredients of this rock are converted partly into relatively insoluble and partly into soluble materials. The felspar, for example, is broken up, and transformed into carbonates of lime, etc., and hydrous silicate of alumina—the former being soluble, the latter insoluble. The augite and olivine, in like manner, yield soluble and insoluble materials. The magnetite and ilmenite, which are often abundant, are not so prone to alteration. Hence when basalt-rocks are finally reduced by epigene action, their relatively insoluble materials are represented by clay, some siliceous sand, and, it may be, iron-ores—the latter often becoming mechanically separated in alluvial deposits as black "iron-sand." Or the iron content of the basalt may be largely carried away in solution as a bicarbonate, and eventually be thrown down as a chemical precipitate. Thus, partly by mechanical and partly by chemical processes, the iron distributed through the original rock as a primary content tends, as the final result of epigene action, to become concentrated. In like manner, other heavy metals and more or less insoluble ores, derived from the disintegration of many different igneous, schistose, and derivative rocks, and from the breaking-up of pre-existing ore-formations, are similarly often concentrated in recent mechanical and chemical accumulations.

The process of rock-disintegration and decomposition, however, is not confined to the earth's surface, but affects the crust at all depths to which water can descend. The rock-changes produced below ground are, of course, almost exclusively chemical. Water descending from the surface often plays a double part. It not only attacks the rocks, leaching out their soluble materials, but, when it becomes a saturated solution, it may redeposit its burden in the pores, capillaries, and more open spaces through which it filters. The solvent power of underground water is rendered evident by the immense quantities of material which are brought up to the surface by springs, and by the cavities which result from the removal of all this soluble rock-stuff. It is further seen in the phenomena displayed by most epigenetic ore-formations—for we can hardly doubt that the contents of lodes, etc., ores and veinstones alike—have, to a large extent at least, been dissolved out of the rocks of the crust at all depths by the action of water. The only conspicuous exceptions among epigenetic ore-formations, are those "contact-deposits" which have been formed directly by the heated vapours escaping from eruptive masses.

From a general point of view, therefore, ore-formations would seem to come naturally under the following divisions :—

1. *Magmatic-segregation Ore-formations.*—Under this head would be classed all native metals and ore-masses occurring as original constituents of igneous rocks.

2. *Magmatic-extraction Ore-formations.*—This division would embrace the various ore-deposits which are genetically connected with eruptive rocks, and are the result of pneumatolytic processes.

3. *Secretionary Ore-formations.*—In this group would be included the great majority of ore-deposits formed underground by the chemical

action of circulating water. The materials of these formations have been derived partly from molten magmas, and partly from the disintegration and decomposition of rock-masses of all kinds, and have been carried in solution and subsequently deposited as chemical precipitates in pores and cavities of every shape, size, and origin. The group would include all cases of metasomatic replacement, impregnation, and dissemination.

4. *Sedimentary Ore-formation.*—Under this head would come all ore-deposits which have originated at the surface, however deeply in many cases they may be now buried, and however much they may have been modified. Here we should group precipitates from aqueous solution formed in lakes, etc., and clastic ore-formations of every kind, whether now occupying a superficial position or occurring as beds interstratified with sedimentary strata of any age. Many of the ore-formations truly interbedded with schistose rocks would be similarly placed in this division.

The mode of formation of the ore-deposits included in groups 1, 2, and 4 is sufficiently obvious and need not be further discussed. The precise origin of many secretionary ore-formations, on the other hand, is often obscure, and has been a fruitful subject of controversy. Many different explanations of their phenomena have been advanced, but of these we need only refer to the two which are at present most in vogue, namely, the theories of (a) *lateral secretion* and (b) *ascension.*

It has long been noted that the mineral contents of a lode are not infrequently influenced by the character of the country-rock it traverses. Thus one and the same lode may be productive while passing through some particular kind of rock, and unproductive when certain other kinds of rock form its walls. In Cumberland, for example, the lead veins are usually highly productive when traversing limestone, but barren when the country-rock is slate. So again, in Derbyshire, the lead-veins generally carry ore when the walls are limestone, while little or no ore appears in those parts of the lodes which pass through the "toadstones" (*todt*, dead, or unproductive), a local name for certain more or less decomposed igneous rocks. This apparent relation between lodes and their country-rock had been variously explained before it began to be suspected that the contents of the veins might possibly have been derived by a kind of lateral secretion from the adjacent rocks. If the materials had originally been diffused through these rocks, it was conceivable that circulating water might have leached them out and redeposited them in open fissures, etc. The researches of Sandberger showed that this suspicion or conjecture was in many cases at least well founded, for, as mentioned above, he obtained traces of not a few of the heavy metals in the minerals of igneous rocks, and also in those of gneiss. He further showed that silica, as well as lime and baryta, compounds of which are so commonly present in lodes, might quite well be derived from several of the original mineral constituents of igneous rocks. So that from the decomposition of such rocks, materials for the formation of many kinds of ore and of the accompanying veinstones might be supplied. He put the matter to the proof by an examination of the ore-formations and country-rock of the Black Forest, and found that the phenomena were in keeping with his expectations. It appeared to him evident, that the nature of the ore-formations was directly affected by changes or variations in the composition of certain mineral constituents of the country-rock. For example, when the mica of the gneiss contained minute proportions of copper, cobalt, arsenic, and bismuth, the lodes yielded smaltite (arsenide of cobalt), and various ores of copper. In other places where the mica of the country rock contained silver, arsenic, bismuth, cobalt, and nickel, and little or no copper, the lodes were found to carry arsenical ores of silver, cobalt, and nickel, but no copper-ore. Although the primary character of the metallic constituents of the silicates analysed by Sandberger has been questioned—the metals being now considered by many to be subsequent introductions—this does not quite invalidate the theory of lateral secretion. That theory explains so many facts, indeed, that it must be to a considerable extent true. Nevertheless, it is not a complete explanation, for it fails to account for certain notable phenomena. If the contents of lodes had always or even often been derived by lateral secretion from the adjacent country-rock, then the former would depend on the nature of the latter to a much greater extent than is found to be the case. Many examples might be cited to show that there is no apparent relation between secretionary ore-formations and the rocks they traverse. For example, several systems of lodes are met with crossing one and the same country-rock, and nevertheless carrying very different assemblages of ores. On the other hand, many lodes cut through rock-formations of all kinds, igneous, sedimentary, and schistose, without showing any marked change in the nature of their contents. Once more, the opposite walls of a lode may consist of totally different rocks (schists, it may be, on one side, and greywacké, sandstone, or limestone on the other), and yet the ores and veinstones may be symmetrically disposed in corresponding layers on the two walls.

Such phenomena as the foregoing occur so commonly that many observers have concluded that the theory of lateral secretion must be abandoned. It seems to them more likely that the contents of lodes have been deposited from solutions ascending from considerable depths. We do not know to what depth water penetrates the earth's crust, but so long as it can find a way for itself there seems no obvious reason why it should not descend until it attains a temperature at which it can no longer exist as water. At what distance from the surface this "critical temperature" (about 690° F.) is reached, can only be roughly conjectured. If the increment of heat as observed in mines and deep borings—1° F. for every 50 or 60 feet of descent—be continued indefinitely downwards, the critical temperature for water would be reached at a depth of over six miles. It is probable, however, that the rate of increase observed near the surface does not continue indefinitely, but is more likely to diminish progressively with the increasing density. If such be the case the critical point for water may not be reached at a less depth than eight miles or more.

At a depth of eight miles or so from the surface it is hardly possible that gaping fissures and cavities can exist. Under the enormous pressure at that depth, the rocks must be in a state of plasticity, and any open space formed during crustal movements would very soon be obliterated by the inflow of its walls. It is only in the upper parts of the earth's crust that water can circulate in open fissures. This region has been aptly termed by Mr Van Hise the *zone of fracture*, and is conjectured by him on various grounds to extend from the surface to a depth of about six miles. At lower depths than this the rocks are in such a condition that even if fractured they would soon be welded together again—open spaces could not exist. In the zone of fracture, open fissures may well extend downwards for great distances, but much will depend upon the nature and geological structure of the rocks they traverse. As these vary much in the resistance they offer to compression, we can readily understand that one and the same fissure may remain open in some parts of its course and be closed elsewhere. Many fissure-veins, as we have learned, show well-defined walls, while the structure of their included ore-formations leaves us in no doubt that the mineral matter has been deposited in what were at one time empty cavities. In many other lodes only one wall is seen, and all the phenomena lead to the conviction that no such continuous cavities existed in their case—the fissures being filled up with crushed and broken rock, amongst the interstices of which the mineral solutions subsequently made their way. Again, in not a few cases, no walls to a lode are visible—a mere narrow crack or close fissure passing through or bounding on one side the ore-bearing rock. In such a case the ore-formation does not occupy a cavity, but impregnates the country-rock on one or both sides of a narrow fissure. All the phenomena of impregnations and disseminations, in short, show us that water makes its way not only along the various division-planes of rocks, but soaks more or less readily through the rocks themselves.

It is not necessary, however, to suppose that the water coming from plutonic depths is of meteoric origin. Indeed, such evidence as we have would lead us to believe that surface-water, in the paucity or absence of open fissures, does not usually penetrate much below 2000 feet. It is the experience of miners in all parts of the world, that deep mines are generally dry and sometimes even dusty. Yet we know that when open fissures in such mines are tapped they not infrequently yield heated alkaline water. It is quite possible that this water may originally have descended from the surface, but, on the other hand, it may have come from plutonic sources. For, as we have seen, all molten rocks contain vast volumes of water-vapour and gases—to the action of which the pneumatolytic phenomena associated with batholiths are obviously due. According to the theory of ascension, therefore, the chief agent in the formation of secretionary ore-formations is probably the heated waters given off by plutonic masses. Not only would these waters (usually alkaline) carry with them mineral solutions derived from the molten magma, but as they continued to ascend they would attack the rocks through which they passed. Finding their way upwards by open fissures of all kinds, they would at the same time insinuate themselves into the narrowest and closest crevices, and permeate the pores and capillaries of the rocks themselves. The various mineral constituents of the rocks would thus become altered, and substances which are practically insoluble at the earth's surface would be taken up. The ascensionist, therefore, pictures to himself such highly heated solutions not only rising through fissures, but being forced under pressure to penetrate more or less deeply the country-rock on either side—thus producing the phenomena of replacement and dissemination. As the water ascends to higher and higher levels, it will continue to deposit mineral matter since its solvent power must become successively diminished by decreasing temperature and pressure. The constituents of the ores and veinstones formed in this way, having usually been carried great distances, will bear no genetic relation to the country-rock on either side of a lode, and will not therefore be influenced by the nature of its walls. To this action of ascending water we must add that of water descending from above, which tends to dissolve mineral matter from rocks near the surface, and finding its way into fissures, must mingle with the water coming from below, and modify the nature of the mineral depositions that take place.

The ascension theory, like its rival the theory of lateral secretion, gives a reasonable explanation of so wide a range of phenomena that it has met with much acceptance. The two theories are really not antagonistic—the one merely supplements the other, although it must be admitted that the great majority of ore-formations, other than those of sedimentary origin and those due to magmatic segregation and pneumatolytic action, are deposits from heated water ascending from plutonic depths. The probabilities are that the metals of ore-formations have been derived in part directly from molten magmas, and in part by secretion from rocks of various kinds, usually at a high temperature and under great pressure, and therefore at very considerable depths, from which they have been carried upwards by ascending plutonic waters.* Secretion, however, has not been confined to great depths, nor has it been effected by plutonic waters alone. On the contrary, it must have taken place at many different levels—at every depth, indeed, to which meteoric water can make its way—and thus the contents of lodes have been influenced again and again by solutions derived from the country-rock at various horizons.

---

* It would appear, therefore, that no hard-and-fast line can be drawn between pneumatolytic ore-formations and secretionary ore-formations—there will be a passage upwards from the one into the other.

CHAPTER XVIII

GEOLOGICAL SURVEYING

Geological Surveying. Field Equipment. Topographical Maps. Data to be Mapped. Various Scales of Maps. Signs and Symbols. Tracing of Exposed Outcrops. Tracing of Concealed Outcrops—Evidence supplied by Soils and Subsoils, by Vegetation, by Form of Surface, by Springs, by Index-beds, by Alluvial Detritus. Carrying Outcrops across Superficial Formations.

It is quite possible to acquire a considerable knowledge of Geology by the mere intelligent perusal of text-books. Without having engaged in practical work, one may even learn to read a geological map, and come to understand in a general way the structure of the region it portrays. Knowledge obtained after this fashion, however, is necessarily superficial, and can never supply the place of personal observation or study in the field. It is only after the student has familiarised himself with the phenomena themselves, that the full meaning of what he may have read about them will dawn upon him. The best counsel, therefore, which one can give a beginner is to commence observation in the field at the earliest opportunity, even before he has gained more than a mere elementary acquaintance with the stony science. Some preliminary knowledge of common minerals and rocks is doubtless desirable, and the student will be all the better prepared for his field-work should he have learned to recognise some, at least, of the more important type-fossils of the several geological systems. Such elementary knowledge, however, is not hard to acquire, and the want of it need not deter him from beginning the study of rock-structure. A profound acquaintance with this important branch of geology has been obtained by several noted observers, who could hardly be said to have had much preliminary training in either mineralogy, petrography, or palæontology.

The best method of getting a grasp of structural or tectonic geology is to attempt the construction of a geological map from one's own observations. There are few more engrossing or interesting pursuits than that of unravelling geological structure, and the investigator will find that the labour involved is amply repaid. For not only does he gain a precise and intimate knowledge of the country surveyed, but he learns to appreciate geological processes and their results as he cannot do in any other way. His conceptions of what is meant by denudation and the origin of surface features; of crustal disturbances large and small; of the metamorphism of rocks, and a thousand other questions will be broad and assured, or narrow and uncertain, according as his knowledge has been derived at first hand from his own personal observation or at second hand from books.

Our first attempts at mapping will likely enough be halting and unsatisfactory, but with zeal and patient endeavour, experience and success will follow. After having devoted due attention to the subject, we may expect in time to acquire such facility in reading and interpreting the stony record, that only one or two rapid traverses of a region may suffice in many cases to disclose to us its geological structure. Indeed, the mere configuration of the ground will often reveal to a trained observer the leading geological features of a country, and enable him to produce a reliable sketch-map. Experts, however, are not infallible, and in rapidly traversing a region may miss important evidence which could not have escaped them had the ground been carefully surveyed.

Field Equipment.—The apparatus required in geological mapping is fortunately neither elaborate nor heavy. There are field-geologists who in some way or other manage to conceal about them all that is essential for the purpose. Others, again, are so elaborately accoutred as to attract the attention of every passer-by. The only necessary apparatus, however, consists of the following:—a hammer, a pocket-lens, a compass and clinometer, a note-book, a stylographic pen, a common lead-pencil, and a good, reliable topographical map.

To these it is well to add a small protected bottle of dilute hydrochloric acid, and, of course, a pocket-knife.

The Hammer.—In the selection of a hammer tastes differ. For general purposes, however, that used by the officers of the Geological Survey can hardly be surpassed.* It should not weigh much over one pound—unless the observer expects to be working principally among hard and tough rocks, such as granite, gneiss, and schists, when it may be desirable to have a somewhat heavier implement. The student will soon learn, however, that there is a certain art even in breaking stones. An adept by one dextrous blow with a light hammer will often strike off a "specimen" from some hard, tough rock, which a tyro armed with a much heavier tool may vainly assail—all his efforts resulting only in the production of so much grit and powder. There is some art not only in the elastic swing of the arm as the blow is delivered, but in the selection of the spot to be struck, which will be determined partly by the shape of the rock-surface and partly by the nature of the rock itself.

If the geologist wishes to collect rock-specimens as he goes along, a heavier hammer will be necessary to detach fragments of a sufficient size, besides which a much smaller tool will be required to trim the specimens to the desired size and shape. To these some geologists add one or more chisels, such as are used by masons. These additional impedimenta may be carried in the strong moleskin bag required to hold his rock-specimens and fossils. Heavily burdened in this way, however, the progress of the hammerer is apt to be impeded; and if his chief object be mapping, he will do well to leave specimen-collecting alone until his survey is completed. After his map is finished, he can devote a few days to gathering such specimens as he wishes to procure. As geological surveying often involves climbing in ticklish places, and much hard walking over rough ground, it is well to go as lightly as one can, if rapid progress be desired. A few capacious pockets to hold the small specimens and chips one may wish to examine carefully at home, will be found more convenient than a bag—the temptation to fill

---

* This hammer is introduced into many of the Plates illustrating this book, see especially Plates X., XXXII., XLIX.

which with choice but weighty material is often too great to be resisted.

The Lens.—This is an important adjunct, and is so easily carried that no field-geologist should be without it. Even the best eyesight may fail to diagnose the finer grained rocks, but there are few of these the character of which cannot be determined by means of a lens. For all ordinary purposes a lens with two powers will be sufficient.

The Compass.—This instrument is primarily used to determine the direction in which strata are inclined, and for this purpose any pocket compass will serve. It is often very desirable, however, to take bearings in order to fix the trend of some dyke, fault, or other structure, or to determine the exact position where some observation is made. This is readily done by means of a prismatic compass. An instrument of this kind, however, is seldom required by the student who is provided with an accurate large scale map, such as the 6-inch map of the Ordnance Survey.

The Clinometer.—With this instrument the angle of dip is measured in the manner already described (p. 127).

The beginner will probably find it most convenient to use an instrument in which compass and clinometer are combined. Being the size of an ordinary watch it slips easily into the waistcoat pocket.* The chief drawback to this instrument is that the edge which is to be held parallel to the line of dip is too short. The edge may be "lengthened," however, by placing it on the note-book, the hammer-handle, or the walking-stick—if the geologist feels it necessary to burden himself with one. He will find ere long that a stick is rather a hindrance than a help, and will probably succeed in losing it before his first day's work is done.

The Note-book.—This should not be too small nor yet too large to slip into a side-pocket. A convenient size is 6 inches by 4 inches—for the book when opened can then be used as a rough-and-ready foot-rule for measuring purposes. The paper may be plain or ruled according to taste. As the book is meant, however, to contain not only notes and descriptions but sketches of geological sections, it is advisable to have

---

* A very serviceable instrument of this kind is supplied by Messrs Troughton & Simms, 138 Fleet Street, London. See Appendix E.

some of the paper ruled into squares. These squares may represent inches, feet, or yards, and thus enable the observer to sketch on a correct scale any rock exposure which can be conveniently measured. Until some facility in drawing has been attained, it is best to use first a common lead-pencil, and afterwards to ink-in the lines. With practice, however, the observer may eventually be able to discard the pencil and to sketch directly with his pen. For clearness' sake it is often advisable to colour a section. Coloured pencils may serve for this purpose, but in a note-book such colours are apt to get rubbed and smudged, and ordinary water-colours, therefore, are preferable. Those who have an artistic aptitude enjoy a great advantage, and can often do without the help of square-ruling—bringing out with a few deftly drawn lines on plain paper all the geological features that call for expression. They can fill their note-books also with sketches of scenery which may show at a glance how the configuration of the ground has been determined by the nature and structure of the rocks. If the observer have this gift, he would do well to cultivate it—for he may be sure that his descriptions of geological phenomena will gain enormously in clearness and value when they are accompanied by well-selected artistic illustrations.

To others who have not been blessed with artistic talent, photography lends much assistance, and is therefore largely indulged in by field-observers—good portable cameras being readily obtainable.

The Topographical Map.—Reliable topographical maps of most civilised countries can now be obtained. In our islands the maps issued by the Ordnance Survey cannot be surpassed for accuracy, and are just such as are desiderated by the geologist. These maps are on various scales—those on the scale of six inches and one inch to the mile respectively being most useful for geological purposes. The beginner will find the larger scale map the more satisfactory of the two, as it enables him to plot his observations in much greater detail than would be possible on the other. The shape of the ground is indicated by numerous contour lines (*i.e.* lines of equal elevation), instead of by "hill-shading," so that pencilled notes and lines are clearly seen, and the observer is usuall saved the trouble of determining heights which, for various geological purposes, it is often necessary to ascertain.

When large maps like those referred to are not available, and the observer has to content himself with maps on a much smaller scale, he may occasionally be compelled to redraw portions of his map on a larger scale. Such will be the case when the geological structures are so highly complicated that they cannot be indicated save in a generalised way on a small map. Every field geologist's note-book is sure to contain enlarged sketch-maps of this kind, showing in detail complex structures which it would be impossible to represent upon any ordinary topographical map. And such enlarged portions of his map may serve subsequently as illustrations to accompany the observer's monograph or paper descriptive of the region surveyed.

The maps of some countries which are only sparsely settled are often little better than generalised sketches, making no pretensions to accuracy; while the topography of many wide regions has not yet been delineated even in outline. Geologists in such cases must be prepared to do some topographical surveying for themselves if they wish to prepare a geological map. In several of our colonies surveying of this kind has been carried on by geologists concurrently with their own special work. Students of geology, therefore, if they intend emigrating, should certainly acquire some knowledge of topographical surveying before leaving home. Even if they have relatively accurate maps provided for them, they may yet frequently find it necessary to correct these or to lay down the topography in greater detail.

Geological Data to be Mapped.—Assuming that the student begins his field work in this country, he has, of course, accurate and detailed maps at his service, which is a very great advantage: for it will readily be understood that when the topography is inaccurate the geological lines cannot be otherwise than distorted. An approximately perfect geological map must, therefore, in the first place, be thoroughly accurate as regards its topography. It should also be on not too small a scale, for the larger the map the greater the detail that can be shown, and the more readily and exactly are geological positions determined. To be of any practical use, a good geological map ought to exhibit the following features, viz. :—

(*a*) The superficial areas occupied by geological systems and their chief subdivisions—the mutual boundaries of the several groups or series being accurately delineated.

(*b*) Individual seams, beds, or formations of economic or scientific interest and importance, such as coals, limestones, ironstones, etc.; the position of available building-stones, etc.; the best sources of underground water-supply; the general character and distribution of superficial accumulations, subsoils, and soils.

(*c*) Igneous rocks—effusive being clearly distinguished from intrusive rocks.

(*d*) Faults, and all fissures which may be supposed likely to contain ore-formations.

(*e*) Dips should be everywhere carefully inserted, so as to show exactly the direction and degree of inclination of the strata.

A map containing these data would enable a geologist, who might never have visited the region represented, to understand at a glance the geological structure. From the details given, he could measure the thickness of the strata, and ascertain the depths from the surface at which particular seams or beds might be expected to occur at given points. He would be in a position to indicate where an underground water-supply might be tapped by borings—all this, and much more, a carefully constructed geological map will reveal to anyone who has the skill to read it. Only large scale maps, such as those issued by the Geological Survey of Great Britain, are sufficiently detailed to be used in this way. The field-observations of the Survey are plotted on the larger Ordnance Map (6 inches to a mile), and the sheets representing the more important parts of the country are published on that scale. The several geological systems and their subdivisions, and the general structure of a region, however, can be quite well represented on a smaller scale. The Geological Survey, for example, issues a general map, on the scale of 1 inch to a mile, the information given on which is, of course, taken from the larger map. Having been carefully reduced from the 6-inch field-maps, the smaller map is sufficiently accurate and detailed for general purposes.

The maps issued by national geological surveys are seldom on a larger scale than 1 inch to a mile, and are usually much smaller. Such maps do little more than represent the broader geological features, the distribution of the several systems and their larger subdivisions, together with the more important developments of igneous rocks, leading lines of dislocation, position of ore-deposits, etc. They are accompanied, however, by more or less elaborate monographs, which contain such detailed information as could not be expressed upon the maps themselves. And the geology of the regions represented on the latter is still further explained by means of horizontal (or profile) and vertical sections, the former being constructed so as to indicate or represent the shape of the surface and the geological structure of the ground, while the latter are designed to show in as great detail as possible the succession of important groups or series of strata, such as coal- or ironstone-bearing formations. (The method of constructing geological sections is set forth in Chapter XXI.)

Small generalised geological maps on a scale of 10 miles to an inch or less, are designed to show merely the distribution of the chief rock-divisions, and have usually been reduced from larger maps. Sometimes, however, outline- or sketch-maps of this kind are original productions, accompanying the descriptions of hitherto unknown or imperfectly known regions. They are meant to do no more than illustrate the pioneer work of geological explorers, and do not therefore make any pretension to minute accuracy.

To the student who would become an expert field-geologist, topographical maps on a scale of less than 1 inch to a mile are of little use. Even a 1-inch map cannot be recommended to one who has all his experience to gain. The beginner who has the good fortune to commence work in this country cannot do better than follow the example of our Geological Survey and use the 6-inch Ordnance Map. Although this map is large enough to allow here and there of notes being inserted, the observer will soon find it necessary to use abbreviations, signs, and symbols. For example,

SIGNS USED ON MAPS OF H.M. GEOLOGICAL SURVEY

Signs connected with the Glacial Drift

 Roches moutonnées (not striated).

 Roches moutonnées (striated), but direction of ice-flow not apparent.

 Roches moutonnées (striated), showing direction of ice-flow.

 Plane or flat surface (striated).

 Plane or flat surface (striated), where direction of ice-flow is visible.

Signs connected with Stratification

 Horizontal

 Vertical (longest line the strike)

 Contorted

} Beds.

 Inclined Strata.

 Gently Inclined Strata.

 Steeply Inclined Strata.

 Cleavage.

 Anticlinal Axis.

 General Dip of Undulating Beds.

 Undulating Strata.

 Synclinal Axis.

Interrupted Lines _ _ _ _ _ show a doubtful or drift-covered Boundary.

White Lines, Faults.

Signs indicating the Ores of the Metals

⊙ Gold.

♄ Lead.

☽ Silver.

 Manganese.

♀ Copper.

♂ Iron.

♃ Tin.

♃ Zinc.

⊕ Nickel.

Gold Lines, Mineral Veins.

instead of writing *sandstones and shales*, *SS* or *Sa & Sh* will suffice. In like manner, most of the common igneous rocks can be indicated by means of the initial letters, as *B* for basalt, *G* for granite, *Sy* for syenite, *D* for dolerite, *Di* for diorite, *P* for porphyrite, and so on. Plate LI. shows some of the signs and symbols used by the Geological Survey of Great Britain and Ireland.

Tracing Exposed Outcrops.—As the most continuous exposures of rock naturally occur upon sea-coasts and along river-courses, it is best for practice to select, if possible, some tract the situation and topography of which seem to promise the observer most information. Proceeding along the sea-coast, and following the stream-courses of a region which we shall suppose consists largely of stratified rocks, the student must insert upon his map the direction and angle of dip as frequently as possible. The outcrops of all notable or important beds and seams (such as limestones, coals, ironstones, etc.) are carefully set down, and particular descriptions of these and the accompanying strata are recorded in the note-book. Fossils are sedulously searched for everywhere, more particularly in the finer grained argillaceous sandstones and shales amongst which seams of coal and ironstone or beds of limestone not infrequently occur. Should any seam or layer be characterised by the presence of certain fossils peculiar to itself, the exact position of such seam should be carefully indicated, for it may be of great service as a datum-line or geological horizon, as will be shown presently. Bedded ironstones and limestones are often marked by the presence of special fossil-forms, and this is one reason why the outcrops of such rocks are invariably mapped by a field-geologist. Any stratum or series of strata, however, which may be notable on account of fossils or lithological character, must be distinguished from immediately overlying and underlying strata. Not infrequently it is possible to separate a great succession of sedimentary deposits into subordinate groups—each, it may be, marked by the presence of particular fossils, or by the composition and structure of the rocks themselves.

Tracing Concealed Outcrops.—After the observer has examined every exposure of rock upon the sea-coast, in river-courses, and elsewhere, and exhausted all the evidence to be obtained in railway-cuttings, quarries, and other excavations, he will usually find that there are wide areas over which no rock appears at the surface. The surface may be concealed under thick soils and subsoils, or overspread by superficial accumulations of various kinds, as clay, sand, gravel, peat, etc. How are such blanks in the evidence to be filled up? How can we carry the lines of outcrops across tracts which are apparently so hopelessly mantled? Fortunately, it is usually possible to follow lines of outcrop even when the rocks themselves are not actually seen, for, although concealed, their presence is often betrayed in various ways. The following are some of the sources of information of which a keen-eyed observer will avail himself:—

(a) *Soils and Subsoils.*—In regions which are not covered by glacial deposits (such as boulder-clay), or by thick sheets of transported materials (sand, gravel, etc.), the soils will usually indicate the nature of the underlying solid rocks, fragments of which are almost certain to occur more or less abundantly. These will, of course, be readily detected in newly ploughed ground, but when the soil is carpeted with vegetation, information is nevertheless often obtainable from worm-castings, mole-heaps, rabbit-burrows, etc. A red, sandy soil containing angular fragments of red sandstone will indicate the presence of red sandstone underneath. Tenaceous clay-soils, with few or no stones, will be found to pass downwards into marls, clays, or argillaceous shales. Should subangular, blunted stones (some of them, perhaps, striated) occur numerously in a stiff clay soil, the presence of till or boulder-clay is indicated. A soil charged with numerous rounded water-worn stones will be found to overlie either a superficial deposit of gravel or a decomposed conglomerate.

In estimating the value of the evidence furnished by surface stones, it is well to remember that if the stones, whether subangular or rounded, should consist of many different kinds of rock, they must be derived from an underlying superficial accumulation of transported materials, or, as just remarked, they may indicate the presence below of a disintegrating conglomerate, the outcrop of which the observer will probably have already encountered in some natural or artificial exposure—say, in sea-cliff, river-course, or railway-cutting. Although a soil be charged with abundant angular fragments of one and the same kind of rock, it does not necessarily follow that the parent rock from which these fragments have been derived, will be encountered immediately underneath the surface. Much will depend upon the configuration or shape of the ground. All soils and disintegrated rock-materials tend to travel downwards from higher to lower levels, and, in this way, soil derived from one kind of rock comes to overlap and to be commingled with soil derived, it may be, from quite a different class of rock-material. The annexed diagram (see Fig. 108) will serve to illustrate this point. Here there are three separate beds represented—*a* being a dark red marl; *b*, a grey sandstone; and *c*, a coarse conglomerate. The soil overlying *a*, which occupies the top of the hill or bank, is red and argillaceous, and as this soil tends to travel down the slope, it invades the outcrop of the stratum *b*, where it becomes commingled with grey sand, derived from the disintegration of the sandstone. There is thus a gradual passage from a pronounced dark red clay soil into a more or less arenaceous soil of a lighter tint—the red colour gradually becoming less and less conspicuous as the base of the slope is approached. It is obvious that angular fragments of grey sandstone may be met with in the soil, at all levels from the outcrop of *b* downwards, while stones from the conglomerate will be confined to the soil that overlies that stratum. This commingling of soil and disintegrated rock-débris along the boundaries of formations is everywhere observable,

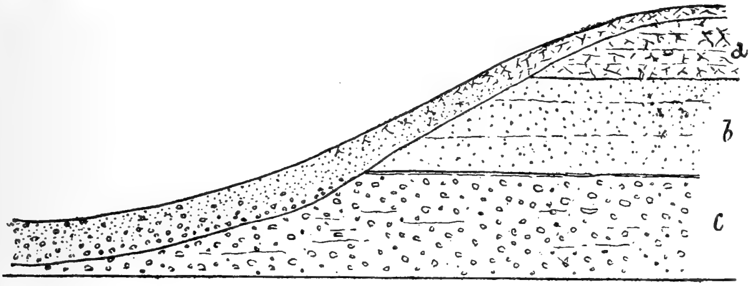


FIG. 108.—TRAVELLING OF SOIL AND SUBSOIL.

and the geologist, therefore, in drawing his boundary-lines, must make the necessary allowances. In the case represented in the diagram there would be no difficulty in ascertaining the boundary lines between the several beds. Walking up the slope the presence of rounded stones would indicate the presence of the conglomerate, so long as even one or two only appeared. Above the junction of beds *c* and *b* water-worn stones would no longer be met with, while fragments of sandstone might continue to abound until the limits of the stratum *b* were reached. The position of the boundary-lines to be drawn would thus be approximately indicated.

Although the colours of soils are invariably due to the character of the rocks from which they have been derived, the observer must remember that the colour of unweathered rocks often differs greatly from that of their disintegrated débris. The brown and reddish colours of many soils are due to the presence of iron-oxides, but such soils are often derived from rocks which are neither brown nor red—these colours having resulted from the chemical alteration of the rocks. Many basic igneous rocks, for example, which may be dark blue or even black, yield yellowish and reddish-brown soils. Again, some kinds of blue and grey boulder-clay are overlaid with reddish-yellow soils. Many impure blue and grey limestones also tend to yield yellowish or brownish soils. Generally speaking, however, the colour of soils formed from the disintegration of derivative rocks does not, for obvious reasons, differ much from that of the rocks themselves.

(b) *Character of Vegetation.*—The character of the vegetation is often an index to the nature of the soil and underlying rocks which the observer cannot always afford to neglect. It is well known that certain plants prefer one kind of soil to another, so that botanists are able to map out a region into areas (not always, it is true, sharply defined), each of which is distinguished by the development of some particular assemblage of plants, or by the presence of certain plants and the absence of others. As the distribution of these plant-societies depends mostly on the chemical and physical conditions of the soil, it is necessarily suggestive to the geological observer. Soils poor in carbonate of lime show a different assemblage of plants from those which are rich in that substance. There are certain species (*e.g.* common bracken, common heather, sorrel, fox-glove, etc.) which avoid calcareous soils; while, on the other hand, not a few species (*e.g.* wild cherry, beech, dogwood, and many flowering plants) are particularly partial to such soils. Porous sandy soils, tenacious clay, loose loams, saline soils, etc., are each characterised by the presence of distinctive plant-groups. In the absence of rock-exposures, therefore, the plant-associations referred to may often be helpful to the field-geologist, and enable him to draw his boundary-lines with more or less confidence. He must bear in mind, however, that the boundary-lines suggested by the varying character of the vegetation will not often coincide even approximately with the junction-line he is in search of. Soils, we have seen, tend to travel down slopes, however gentle these may be, and in this way a soil rich in lime may eventually come to overlie a quartzose sandstone which might contain hardly a trace of lime; just as, on the other hand, a barren, infertile sand may in time invade and cover rocks, which, if left exposed to the weather, would naturally have yielded a highly fertile soil.

Nevertheless, the observer who has a sufficient knowledge of botany will not infrequently have occasion to turn this knowledge to good account. Having ascertained the character of the flora which he finds growing upon soils in places where their derivation from the underlying rocks can be seen, as it were, taking place, the appearance of a like plant-assemblage elsewhere will lead him to suspect the presence of the same rocks below, although none of these may be actually visible at the surface.

(c) *Form of Surface.*—The shape or configuration of the ground is frequently of great service in showing where a boundary-line should be drawn. As will be set forth more fully in the sequel, the forms assumed by a land-surface are determined in chief measure by the nature of the underlying rocks and their geological structure. Rocks differ greatly as regards durability—some being much more readily reduced than others by the superficial agents of change. Hence, in regions which have been long exposed to denudation, the less readily disintegrated rocks tend to project, while the more yielding kinds are correspondingly worn-down or levelled.

It is matter of common knowledge, indeed, that hills and ridges are usually, or at least very often, built up of relatively harder or more resistant rocks than those that occupy contiguous, low-lying tracts. This, however, is not invariably the case, as will be shown later on. Not infrequently the hills of a country consist of no harder or less readily disintegrated rocks than are found in the low grounds. In a great many cases this is due to the geological structure or arrangement of the rocks. There are certain structures that tend to resist while others favour denudation. Hence, a series of strata having the same consistency throughout, may in some places form hills, while elsewhere they may occupy depressions of the surface. In the above diagram (see Fig. 109), for example, it is obvious that the position of the hills has been determined by the strong synclinal arrangement, while the weaker anticlinal structures have been more readily reduced. If the observer be geologising in a region where the rocks are inclined for long distances in the same direction, he will usually find that the outcrops of relatively harder beds tend to project more than those of the less durable strata amongst which they are intercalated. Hence, even when the naked rock is concealed by vegetation and soil, it nevertheless will form a feature. Thus, in the accompanying section (Fig. 110), we have a series of limestones and shales, the outcrops of which are not actually seen, and yet their position is indicated

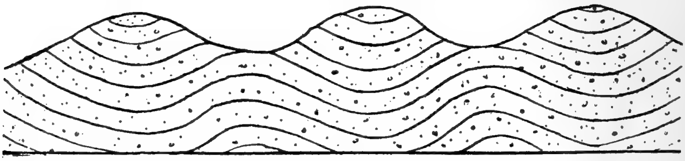


FIG. 109.—SURFACE-FEATURES IN GENTLY-FOLDED SANDSTONES.

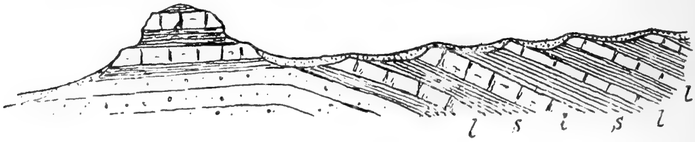


FIG. 110.—FORM OF GROUND INFLUENCED BY GEOLOGICAL STRUCTURE.

by the form of the ground. It is obvious, indeed, that the occurrence of a thick bed of relatively hard rock intercalated in a series of softer or more yielding strata, inclined in one and the same direction, must, under the influence of denudation, give rise to the formation of escarpments or ridges—which, whether the naked rock be actually exposed or not, will form prominent features in a landscape. In the case of countries which are built up of horizontal strata, the varying hardness of the rocks will similarly affect the form of the ground, and cause it to assume a terraced aspect—a structure illustrated in the same diagram (Fig. 110), where the gentler slopes correspond with the outcrops of "soft" rocks, and the more abrupt gradients with the outcrops of "hard" rocks.

It must be borne in mind, however, that in countries heavily covered with glacial and other superficial accumulations, the surface configuration of the underlying solid rocks is often obscured or even entirely concealed. But when such deposits are either absent or attain no great thickness, the form of the ground is always of the greatest assistance to the geologist who is trying to carry a line of outcrops across a country.

(d) *Springs.*—Considerable aid in tracing boundary-lines is sometimes afforded by springs. When layers of relatively impervious materials, such as shales, clay, etc., are intercalated among a series of porous strata, underground water tends to come to the surface along the line of junction between the porous and the non-porous strata. This will often happen when bedded rocks are truncated by the slope of the ground, the water appearing in the form of springs or oozing out slowly and giving rise to marshy and damp spots. Should a number of such springs or seepage-places occur in succession in some given direction, they will necessarily indicate the presence of a geological boundary-line. Occasionally, spring-water is highly charged with mineral matter, such as carbonate of lime, iron-oxide, etc., and hence deposits of calc sinter, bog-iron ore, etc., tend to be formed at the surface along the junction between porous and impermeable strata. (For a more particular account of springs, see Chapter XXIII.)

(e) *Index-beds.*—Although it is true that the most continuous exposures of rock are to be met with along the seashore and in river-valleys, it nevertheless often happens that, owing to the presence of superficial accumulations, the rocks in a valley may be concealed for longer or shorter distances. But should the observer have previously examined the strata over a considerable area, the occurrence of such blanks in the evidence does not necessarily disconcert him. He probably recognises, in the few sections available for study in some particular valley, portions of a series of beds, the stratigraphical position of which has already been revealed by more continuous sections exposed elsewhere in the same district. After he has carefully studied the strata of a wide area, he will frequently find that a great thickness of strata may show a monotonous alternation of the same kinds of rock, say, sandstones and shales, and yet these may exhibit sufficient variety of lithological character to allow of the whole series being roughly divided. Perhaps thick-bedded coarse-grained sandstones and grits with subordinate shales may prevail at one horizon, and shales with occasional thin beds of fine-grained sandstones may predominate elsewhere. Possibly, also, the shales at stated intervals may contain nodules of a particular kind, or there may occur at a definite horizon some stratum characterised either by its fossils or by certain peculiarities of composition, texture, or structure. Beds of this kind are not infrequently persistent over considerable areas, and when such is the case they are invaluable to the field geologist. They may not be of sufficient importance to be mapped separately from the series in which they occur, but their presence in a section at once indicates the stratigraphical horizon. Should the observer have ascertained that an "index-bed" of this nature lies at a given distance above or below any limestone, coal, or other valuable seam he may be desirous of mapping, it is obvious that the appearance of the index-bed in a valley must enable him to fix the approximate position of the seam he is in quest of—no matter how deeply the outcrop of the latter may be buried under alluvium. The field-geologist, therefore, cannot be too careful in acquiring a full knowledge, not only of the particular beds whose outcrops he seeks to trace, but of the varying characters of the several groups or series of strata with which those beds are interstratified. An adequate detailed acquaintance with the whole series of rocks occurring in a district often enables the observer to locate the geological horizon of isolated rock-exposures, and to plot the position of boundary-lines with wonderful accuracy, even in places where the ground is thickly mantled with superficial deposits.

(f) *Transported Detritus in Stream-courses.*—In cases where the geological position of the rocks exposed in a stream is not suggested by the character of the rocks themselves, the field-geologist does well to examine carefully the gravel and detritus, as he proceeds up the valley. Should he detect fragments of a rock, say, limestone, which he has already encountered *in situ* elsewhere in the same district, he makes careful note of his find and continues to follow the spoor up-stream. Possibly the limestone fragments become more and more numerous as he goes on his way, while, at the same time, they are less water-worn, and occasionally, perhaps attain a relatively large size. Eventually, at some particular spot they cease to occur—the obvious inference from which is that the limestone itself must crop out here or at some short distance up-stream. In a case of this kind a geologist would naturally seek to strengthen the evidence by carefully examining the adjacent valley-slopes for similar angular fragments.

After direct and indirect evidence of every kind has been exhausted, we probably find that there are still certain spaces upon our map across which boundary-lines cannot be traced. Wide sheets of peat or alluvium, for example, may effectually conceal broad areas. Should the map we are using be on a large scale, say 6 inches to the mile, we should stop the lines abruptly where they meet the obscuring sheet of alluvium or peat, and colour the latter as a separate formation. On small-scale maps, however, it may be desirable in many cases to carry a line—more especially if it be the outcrop of some important or valuable seam—across areas which are covered by peat or alluvium. This may be safely done when we have assured ourselves that there is no interruption or break in the continuity of the strata. When the conditions are such as represented in Fig. 111, there can be no doubt that the outcrop of the limestone (*a*) must continue across the area concealed by the peat (*x*), seeing that the outcrop of the upper limestone (*b*) has been followed without interruption from west to east, while there is clear evidence of a continuous succession of strata between *a* and *b*.

In all cases, however, where an outcrop is inferred from indirect evidence, a conscientious and cautious observer will be careful to indicate this by drawing dotted or interrupted instead of continuous lines. Continuous lines should mean that the outcrops are actually visible—that the rock can be seen *in situ;* while interrupted lines should merely indicate the position at or near which the observer thinks it likely that the outcrop may be found.

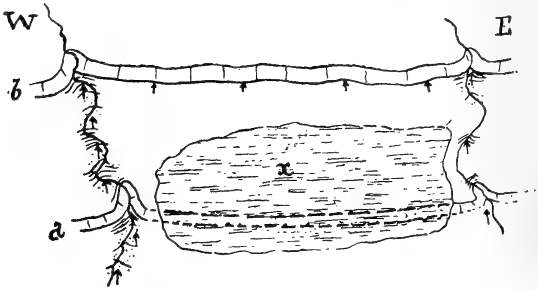


FIG. 111.—CONCEALED OUTCROPS.

CHAPTER XIX

GEOLOGICAL SURVEYING—*continued*

Forms of Outcrop. Measurement of Thickness of Strata. Thickening and Thinning of Strata. Unconformity. Overlap. Normal Faults. Reversed Faults. Eruptive Rocks and Contact Metamorphism. Regional Metamorphism. Archæan Gneissose Rocks.

Forms of Outcrop.—The form and direction of an outcrop naturally vary with the configuration of the ground and the direction and angle of dip. As a rule, the most winding and sinuous outcrops appear among horizontal strata, especially when these have been deeply trenched and eroded. Gently inclined strata also frequently yield very sinuous outcrops, while the outcrops of steeply inclined and vertical beds are usually more regular in their trend, and sometimes run for long distances in approximately straight lines.

Horizontal Strata.—In the case of an undulating plateau built up of horizontal strata, and traversed in different directions by many valleys, the outcrops necessarily follow all the windings of the latter—they play the part, in short, of contour-lines. The width of the outcrops is determined, of course, by their position with regard to the configuration. Thus, upon a steep slope, an outcrop of a stratum many feet or yards in thickness will be indicated upon the map by a relatively narrow band or ribbon, while the outcrop of the same stratum occurring on the top of a hill would be represented by the whole surface of the bed, which might form quite a broad patch of colour on the map.

Inclined Strata.—The outcrops of inclined strata also vary in direction with the shape of the ground, but they are influenced likewise by the angle of dip—an influence which becomes less and less marked as the dip increases. The width of individual outcrops similarly varies with the degree of inclination: beds dipping at a low angle yielding a relatively broad outcrop, while the same beds dipping at a high angle present a relatively narrow outcrop. Thus the outcrop of a bed of uniform thickness will appear broader or narrower as the dip diminishes or increases.

Vertical Strata.—The outcrops of vertical beds are practically uninfluenced by the form of the ground, and display, of course, the true thickness of the strata.

Measurement of Thickness of Strata.—When strata are horizontal, it is obvious that their thickness can only be

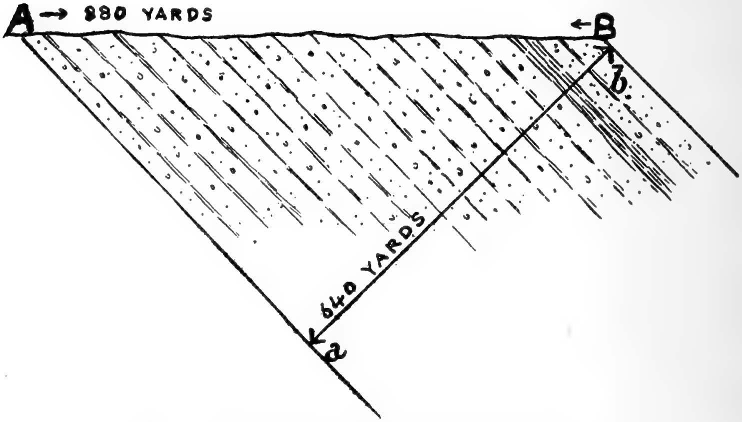


FIG. 112.—MEASUREMENT OF INCLINED STRATA.

measured when they are exposed in section, as in sea-cliffs, river-valleys, etc. If we know the heights above sea-level reached respectively by the lowest and uppermost beds of a great series of horizontal strata, we of course know at the same time the thickness of the strata. So, again, in the case of vertical strata it is obvious that a line measured exactly across the strike of the beds will give us their thickness between any two selected points. But when strata are inclined, the width of their outcrop is necessarily greater than the actual thickness of the beds. By means of a protractor, however, there is no difficulty in measuring the thickness of a series of strata, inclined at a known angle between any two given points. Thus, in the diagram (Fig.

112), we have a series of beds dipping from A to B at an angle of 45°. The section is on the scale of 6 inches to the mile, so that the width of the outcrop between A and B is 880 yards, or half a mile. All that we need to do, then, is by means of a protractor to draw lines in order to show the exact inclination of the beds at A and B respectively; thereafter, another line drawn at right angles to the dip from *a* to *b* gives the thickness of the series (640 yards). From A to B the beds dip continuously at the same angle, but this is not very often the case; more commonly the dip is apt to vary in amount from place to place. When this is so, all we can do is to take the average angle of inclination, and from that we get approximately the true thickness.

The following rule, given by Charles Maclaren in his well-known *Geology of Fife and the Lothians*, may be found serviceable in estimating thicknesses in the field. If the breadth of inclined strata be measured across their outcrop at right angles to the strike, their true thickness will be equal to $\frac{1}{12}$th of their apparent thickness for every 5° of inclination. Or the rule may be put thus: divide 60 by the dip, and you obtain the fraction which expresses the thickness. Thus, suppose a series of strata measures across the strike 1200 feet—if the dip of the beds be 5°, their thickness is $\frac{1}{12}$th, or 100 feet; if the dip be 10°, the thickness is $\frac{1}{6}$th, or 200 feet; with a dip of 15° we get a thickness of $\frac{1}{4}$th, or 300 feet; and a thickness of $\frac{1}{3}$rd or 400 feet, when the dip is 20°. The rule is not quite correct when the dip exceeds 45°.

Thickening and Thinning of Strata.—When the observer has completed the drawing of his boundary-lines and outcrops, and clearly established the true succession of the strata, he will often find that the interval between the outcrops of two separate seams or beds varies from point to point. In other words, the intermediate strata seem to thicken out or to thin away, according as the outcrops are followed in one direction or another. Now this apparent increase or decrease may sometimes be accounted for, as we have seen, by inequalities of the surface, or by variations in the angle of the dip. If we have satisfied ourselves, however, that the mutual approach or retreat of the outcrops is not due either to the form of the ground or to increase or decrease in the degree of inclination, then we may conclude that it is owing to an actual thinning-away or thickening-out of the intermediate strata.

Unconformity.—This structure is readily revealed by mapping the ground, even although it may never be shown in any actual section. The accompanying diagram (Fig. 113) represents the ground-plan of an unconformity. Here there are two series of strata inclined in different directions—one set is said to "strike at or against" the other. It is obvious that the series A cannot possibly belong to the series B. There is no room, so to say, for the beds A to swing round (between *a* and *x*) and dip underneath B. The junction between the two series must, therefore, be discordant, and, if not due to faulting, can only indicate an unconformity. If the observer have reason to suspect an unconformity, he must carefully look for such evidence as is referred to in Chapter XII.—where the phenomena of unconformity and overlap are described.

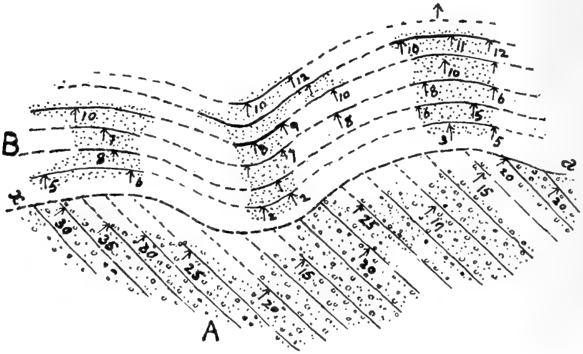


FIG. 113.—GROUND-PLAN OF AN UNCONFORMITY.

Continuous lines = outcrops and boundaries exposed in section. Interrupted lines = inferred positions of outcrops and boundaries. Stippling = rocks exposed at surface.

Overlap is not readily shown upon a plan except when it accompanies well-marked unconformity. Mapping almost invariably discloses the structure, however, when it occurs on a considerable scale. Small local overlaps may readily be overlooked, but when the structure characterises a wide area it can hardly be missed. In Fig. 114, which is a ground-plan of an unconformity and overlap, the latter structure is not shown in the area traversed by the section line A—B. Here no appearance of overlap is apparent, but as the outcrops are followed towards the area C D, the bed *b* gradually overlaps the bed *a*, while the former is overlapped by the sandstone *c* which come to rest directly, and with a strong unconformity, on the highly inclined strata S S. The section C D shows the overlap and unconformity—*b* overlapping *a*, and being in turn overlapped by *c*.

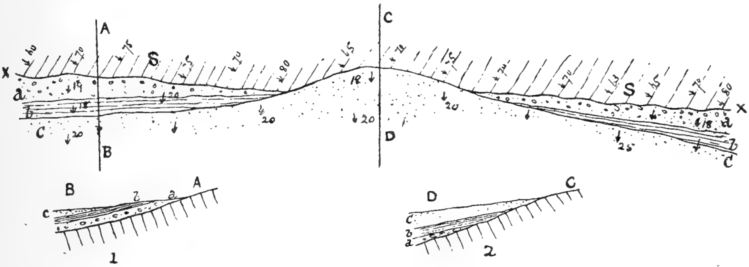


FIG. 114.—GROUND-PLAN OF UNCONFORMITY AND OVERLAP.

S S=Silurian strata ; x x, unconformity ; *a*, *b*, *c*, =younger series of strata showing overlap ; 1. Section along the line A—B ; 2. Section along the line C—D.

Normal Faults.—Faults are not infrequently observed in natural sections, but these, as a rule, are small downthrows of little importance. The larger dislocations of a faulted region may now and again be encountered in railway cuttings and other excavations, but they are rarely observed in natural rock exposures. One reason for this is obvious enough: highly shattered rocks are usually associated with great faults, so that when these are exposed by denudation the shattered materials readily fall asunder and the actual fracture becomes concealed. Or the shattered rocks on one or both sides of the fault being easily broken up and removed by epigene action, a hollow may be washed out along the line of dislocation, and form eventually a receptacle for alluvium and other products of surface erosion. Many faults fail to show at the surface of regions which, like our own, have long been exposed to denudation, simply owing to the fact that any inequalities of surface which may originally have been caused by such dislocations have long ago been planed away, and the ground has become more or less swathed in soils, subsoils, and superficial accumulations of every kind. Although denudation tends in this way to reduce a land-surface generally, nevertheless it is obvious that hard rocks will not be so readily reduced as soft rocks. Thus any marked or sudden change in the form of the ground will be due in most cases to an abrupt change in the petrographical character or the geological structure of the rocks. In most cases the low grounds will be composed of weakly arranged or of relatively soft rocks, while the higher ground will indicate the presence of harder rocks, or stronger structures better fitted to withstand the destructive action of epigene agents. As one frequent result of great faults is to bring relatively soft and hard rocks together, we may expect to find that such faults, although not actually seen in section, have yet influenced the form assumed by the ground under the influence of denudation—the hard rocks will tend to project above the level of the relatively soft or less durable rocks.

Abrupt changes in the form of the ground may be due, however, to other structures than faults—the more important of which are the following:—

(*a*) An abrupt change of level may be caused by the outcrop of a relatively durable stratum occurring in a series of less durable strata. In the annexed diagram (Fig. 115) we have the structure known as escarpment and dip-slope—one of the commonest forms of land-surface, especially in regions of moderately inclined strata. Now and again the dip of the strata, instead of being towards the high ground as in escarpment-structure, may be in the opposite direction. This occurs when a thick series of relatively hard rocks are overlaid by softer strata. The former, as in other cases, tend to form a line of heights, but the descent from these to the low grounds is usually less abrupt than in the case of escarpments (see Fig. 116). In both cases the lines of elevation caused by such outcrops may be either very sinuous or approximately

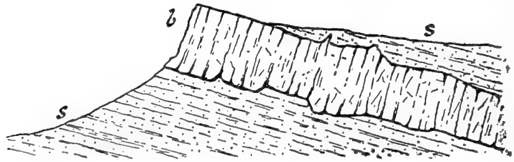


FIG. 115.—ESCARPMENT AND DIP-SLOPE.
b, dolerite; *s*, sandstones and shales.

straight—according as the strata are gently or steeply inclined. If an escarpment be due to the outcrop of such a rock as limestone it will usually extend for some considerable distance. If, on the other hand, it has been determined by the presence of a sill or a thick conglomerate, its lateral extension will probably be limited.

(*b*) A sudden change in the form of the ground may indicate an unconformity (see Fig. 113), where a series of "soft" rocks (B) repose on the truncated ends of much older and more indurated strata (A). In a case of this kind the line of high ground will usually be more or less sinuous and irregular, for it simply represents a former coast-line, the younger rocks ever and anon extending into what were old bays and inlets. Evidence of so well-marked an unconformity as this could hardly escape an observer; but in nature the proofs of unconformity are not always so conspicuous.

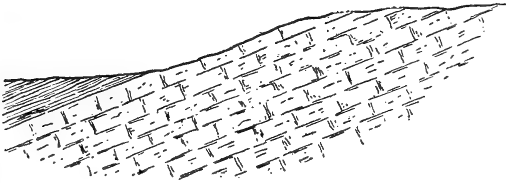


FIG. 116.—INCLINED "SOFT" ROCKS OVERLYING "HARD" ROCKS.

The observer who encounters a sudden or abrupt change from low to high ground, and has satisfied himself that the form of the surface cannot be explained either by the occurrence of interbedded hard rocks, of intrusive rock, or of an unconformity, will be justified in suspecting the presence of a fault. If a fault be present, then the line separating low and high ground will be somewhat straight or very gently sinuous, while seepage of water and more or less numerous springs will probably occur, and so indicate the position of the actual line of fracture. When the presence of a fault is thus suspected, the field-geologist will carefully search for the more direct evidence, some account of which has been given in Chapter XI. The fault itself, if it be one of considerable displacement, will probably not appear in section, but he may find that the strata seen in the low ground become more or less abruptly turned up at high angles of inclination as he approaches the base of the hilly ground, until, at last, they may stand on end. Should such be the case, the strata so disturbed will probably be abundantly shattered and traversed in all directions by irregular joints, the faces of which will frequently show slickensides and be coated with mineral matter. In short, veins of quartz, calcite, etc., may ramify more or less abundantly through the disturbed rock-masses. When the strata on both sides of the inferred fault are mapped, the observer will most likely find that the two sets of rock "strike at" each other—the outcrops of one, or it may be of both series, being truncated, as shown in the accompanying ground-plan (Fig. 117). The determination of the downthrown side of a very large fault is seldom doubtful. If the relative age of the strata on either side of the dislocation be known, and this is usually the case, the younger rocks will, of course, occur on the downthrow side. In cases where faults traverse one and the same series of rocks, and are not exposed anywhere in section, the downthrow side of a dislocation will yet be rendered evident by the effect produced upon the outcrops, as already described (Chapter XI.).

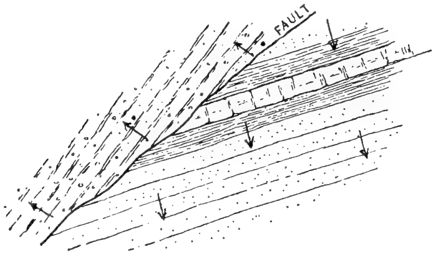


FIG. 117.—FAULTED STRATA STRIKING AT EACH OTHER.

Reversed Faults.—Reversed faults occurring amongst strata the geological age of which is known are not hard to detect. When Carboniferous rocks, for example, are seen dipping regularly underneath Devonian beds, it is obvious that this inversion of the stratigraphical succession must be due either to overfolding, or to an overthrust, or to a combination of both structures. If the inversion be the result of folding alone, then it is obvious that both series of rocks occurring in the reversed limb of a strongly unsymmetrical or recumbent fold must be turned upside down. If, on the other hand, the inversion has been caused by a reversed fault alone, then there will be no overturning of the beds in either series of strata, the individual beds of the Carboniferous will occur in regular sequence, and the same will be the case with the Devonian strata. But, as reversed faults have frequently resulted from the yielding of unsymmetrical folds, it often happens in cases of inversion that this structure shows a combination of overturning and overthrusting.

Folding and faulting of such extreme kinds are usually best developed in regions which have been subject to great deformation—regions the structural geology of which can hardly be unravelled by the tyro. The observer, who is prepared to work out complicated structures like those of N.W. Scotland, the Alps, etc., has got far beyond the need of an elementary hand-book. The beginner, however, who is anxious to become familiarised with the phenomena likely to be encountered in regions of complex structure, can hardly do better than study the beautiful maps of Wester Sutherland and Ross, which have been issued by the Geological Survey. With these maps before him, and with the help of the works mentioned in the footnote, the student will have some idea of the nature of rock-structures which are characteristic of "folded mountains." *

Eruptive Rocks.—The mapping of eruptive rocks is carried on in the same way as that of sedimentary strata. The outcrops of contemporaneous or effusive igneous rocks are not more difficult to follow than those of limestone or any other bedded rock. The boundary-lines of intrusive bosses, sills, and dykes, however, are more irregular, and, in the absence of sections, may sometimes be hard to trace. Rocks of this class, however, are usually more resistant than the rocks they traverse, and thus tend to project and form conspicuous features at the surface. In mountainous regions where the rocks are generally well exposed, the field-geologist is more likely to be troubled with the abundance than with the paucity of the evidence. In the case of a mass of granite, for example, the junction-line is apt to be very irregular—larger and smaller veins penetrating the adjacent rocks in all directions. The details of structure are often, indeed, so intricate that the most the observer can do is to generalise

---

* The sheets of the 1-inch map are as follows :—81, 91, 101, 107, 114. Consult *Annual Reports of the Geological Survey*, 1892-96 inclusive ; *Summary of Progress of H.M. Geological Survey for* 1897. See also *Quarterly Journal of the Geological Society*, vols. xliv. 378 ; xlviii. 227 ; l. 661. The whole region is described in great detail in the Geological Survey's Memoir—*The Geological Structure of the North-West Highlands of Scotland*, 1907.

these, drawing his lines so as to show the shape of the mass—whether it be circular, elliptical, or quite irregular, or following in a rude way the strike of the surrounding rocks. The numerous veins, etc., must be generalised, but when well exposed in section or in plan, it is advisable to make careful drawings of these for future reference, when the phenomena come to be described. So far as he can do so, the observer will try to indicate upon his map the nature of the altered rocks which surround the granite. The stages of contact-metamorphism, however, so frequently graduate into each other, that it is often quite impossible to draw boundary-lines separating one kind of metamorphic rock from another. Nevertheless this can sometimes be done, more especially in cases where the original unaltered rocks have differed markedly in character, and have thus been metamorphosed into more or less strongly contrasted sub-crystalline and crystalline rocks. There are many other observations that the field-geologist will find it impossible to indicate upon a map, but which he should not fail to describe in his notebook.

Sills are not, as a rule, hard to trace. Even when the actual lines of junction with adjacent rocks are not exposed, the intrusive character of a sill is frequently indicated by the way in which it seems to steal across the strike of the strata. The absence of any bedded tuff accompanying the igneous rock, would be so far suggestive of the intrusive character of the latter. This negative evidence, however, would be much strengthened if veins of the same kind of rock were found penetrating the overlying strata. We could hardly doubt in that case that the veins were genetically connected with the igneous rock, and that the latter therefore was not truly bedded, but an intrusive sheet or sill. *Dykes* are even more readily diagnosed in the field than sills, and can usually be followed without difficulty. Their presence is often revealed by lines of springs which come to the surface on that side of a dyke towards which the strata are inclined. For the various details of structure and the general phenomena characteristic of sills and dykes, however, reference should be made to Chapters XIII. and XIV.

The same chapters also give some account of *Necks* or pipes of eruption. When these structures are seen either in plan or in section, their character is at once revealed. Sometimes, however, the actual line of junction between them and the rocks they traverse is entirely concealed, and in such cases they might possibly be mistaken for outliers. Fig. 118, for example, shows in ground-plan field data which are so apparently incomplete that the agglomerate and tuff *a*, might be explained as an outlier resting unconformably upon the truncated ends of the strata *b*. We should have no doubt, however, as to its intrusive nature if we could make the following observations:—1. The tuff either shows no bedded arrangement, or, if any trace of bedding be visible, the dip of the rude layers is towards the centre of the mass; 2. Dykes or veins of crystalline rock traverse the tuff, while similar veins of the same rock appear at some little distance invading the adjacent rocks; 3. The surrounding strata as they approach the tuff are more or less shattered, and perhaps show traces of induration as if from the action of heat. Should the portions exposed be not far from the concealed junction, the beds may appear suddenly to bend over so as to dip abruptly towards the agglomerate or tuff; 4. Fragments of the adjoining rocks and of rocks which may be recognised as belonging to lower and higher geological horizons, can be detected in the tuff. Evidence of this varied kind would satisfy us that the igneous rock was not an outlier but a neck, and we should be justified in drawing around it an interrupted line.

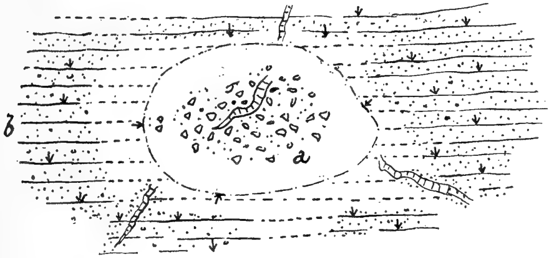


FIG. 118.—GROUND-PLAN OF NECK.
Continuous lines and arrows = boundaries and dips exposed in section. Interrupted lines = conjectural positions of boundaries. Stippling, etc. = rocks exposed at surface.

Occasionally, necks are occupied wholly by crystalline rock, the junction between which and the adjacent rocks may similarly be concealed, so that the observer may be in doubt at first as to whether the igneous rock may not be an isolated patch or cake resting unconformably on the strata that crop out in its immediate neighbourhood. Were such its origin, its jointing should be vertical. On the other hand, if it be of the nature of a plug occupying a pipe of eruption, the joint-planes will be arranged horizontally. A geologist having satisfied himself on this point would, of course, seek to strengthen the evidence by such additional observations as are referred to above in connection with necks of agglomerate.

Slaty Cleavage.—This structure, we have seen, occurs among rocks which have been more or less folded and compressed. In fine-grained slates the original planes of lamination and bedding are usually obscured, and may even be entirely obliterated, and when such is the case the superinduced cleavage-structure might readily be mistaken for planes of sedimentation. The geologist, therefore, must be on his guard, and when any thick belt of finely divided argillaceous rock is encountered in a region of steeply inclined and much-folded strata, he should at once suspect that the division-planes may be those of cleavage. If the rock be really a slate, careful examination will probably result in the detection of the original lines of bedding. These may be indicated by alternating bands of differently tinted slate or by variations in the texture of the slates—such differences of colour and texture being visible in section, as it were, on the cleavage-planes. By splitting the slate open we can see that the varying tint and texture are not merely superficial but, penetrating the rock, are as conspicuous on one face of the slate as on the other. Usually, however, bands and beds of greywacké, quartzite, or other less cleavable rock occur interbedded with slates—and the presence of these at once discloses the true bedding. It is not uncommon, moreover, to find the cleavage-structure restricted to the argillaceous rocks of a series of folded strata, and as the structure in question frequently traverses the original bedding-planes at a high angle, the junction between cleaved and non-cleaved rocks often resembles an unconformity (Fig. 119). In

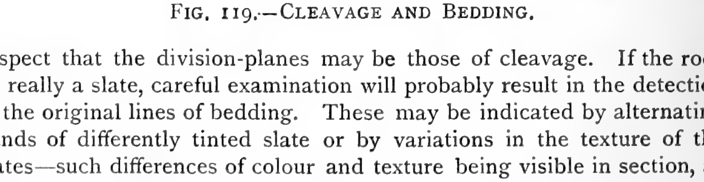


FIG. 119.—CLEAVAGE AND BEDDING.

mapping slates, therefore, the chief danger to be avoided is the mistaking of cleavage for bedding. It is necessary, however, always to note the direction of the strike and dip of the cleavage-planes, especially when the bedding is obscure or obliterated. For the strike of the cleavage coincides more or less closely with the axes of folds and plications, and is thus helpful in unravelling the geological structure of a complicated region.

Regional Metamorphism.—Not much need be said on the subject of mapping an area in which regional metamorphism has been developed—the structural geology being frequently highly complicated and obscure, and hardly to be attempted by one who is not well versed in petrography, and has had little experience in geological surveying. Nevertheless, even a beginner will find much to interest him in trying to puzzle out the structure of such a region.

We have already learned that regional metamorphism is not infrequently a result of deformation. In other words, the rocks of such a region have been more or less compressed and buckled up or folded, and in many places have yielded to tangential squeezing and crushing, whereby overthrusts on a grand scale have often been effected. In mapping an area which exhibits such phenomena, it is obviously most important that we should be able to lay down the axial lines of the chief folds, and the position of all considerable thrust-planes. This may be done without troubling ourselves at first as to purely theoretical questions concerning the particular chemical and mineralogical changes through which the rocks may have passed. It is more than likely, however, that as we proceed with our field observations we shall be confronted with evidence that may go a long way to show not only what the original character of the rocks may have been, but to reveal the successive changes which some of them have undergone.

Bearing in mind, then, that the rocks, whatever their original character may have been, are arranged in folds, we shall expect to find the position of these indicated by the outcrops of more or less persistent zones or belts of different kinds of schistose rocks, all having approximately the same trend. These bands, we may safely assume, represent the general strike of the series. Not infrequently, however, we may traverse wide areas throughout which only a monotonous succession of one and the same kind of rock may appear. Nevertheless, if our traverses be sufficiently extensive, we may expect ere long to meet with other types of rock, the relative position of which will enable us to determine the general strike or alinement of the whole complex. The observer must be on the constant outlook for bands of rock which are characterised by the presence of minerals peculiar to themselves. Knowing that the production of these minerals is due in all probability to some peculiarity in the composition or constitution of the original rocks, their presence may sometimes be as useful in working out a stratigraphical succession as the occurrence of fossils in a series of unaltered strata. Beds and bands of ores not infrequently occur in connection with particular kinds of schist, and have in certain regions, as in Norway, been followed over wide areas, and as these ore-bearing rocks are everywhere associated with the same kinds of schist, there can be no doubt that they are truly stratiform, and indicate a definite geological horizon. Crystalline limestones and dolomites interbedded with certain distinctive kinds of schist have in like manner often been traced for long distances, and when similar calcareous bands accompanied by the same varieties of schist are found cropping out at what might appear to be either lower or higher horizons, the probabilities are that such successive outcrops are simply the result of folding, the same beds coming again and again to the surface.

It is not unlikely that the observer, while traversing a region of schistose rocks, may occasionally encounter areas of less highly metamorphosed strata. He may be able to recognise well-marked clastic rocks, such as schistose conglomerate, quartz-rock, phyllite, greywacké, limestone, etc. Should such be the case, the strata must be carefully followed along and across the strike, for the purpose of tracing the changes they undergo as the region of more highly metamorphosed rock is approached. The successive bands or zones of distinctive schists which we may already have traced through this latter region, we may now be able to connect with particular beds occurring in the area of less altered rocks. Should such be the case, we shall have no reason to doubt that the schists are metamorphosed sedimentary strata; and should the direction of their foliation coincide with the dip of the individual bands, we shall be justified in concluding that the schistose structure has been developed along original planes of bedding. This is most likely to be the case when isoclinal folds have been closely compressed, so that the rocks are either on end or disposed in highly inclined positions. When the folds open out, foliation—often following planes of cleavage—must sometimes have coincided with, and sometimes have traversed, the original bedding at various angles. Therefore, the mere direction of the planes of foliation, when all trace of bedding has been obliterated, cannot, in the absence of other evidence, be relied upon as revealing original stratification.

Just as the observer must be on the outlook for every item of evidence that seems to indicate the arrangement of metamorphosed strata, and to reveal the original character of the beds, so he must endeavour to ascertain what relation the eruptive rocks he may encounter bear to the schists they traverse. If they are older than the metamorphism, then they themselves will have undergone some change, and may be as highly crushed and foliated as the schists. If, on the other hand, they are of later date, they will not be metamorphosed. Possibly the geologist may encounter igneous masses of older date than the metamorphism, which, nevertheless, have a normal appearance. When such masses, however, are followed for any distance they will doubtless begin to show traces of crushing, and eventually pass into schists or gneisses as they near the region of extreme metamorphism.

Both normal and reversed faults may appear among schistose rocks—indeed, faults and extensive thrust-planes may almost be expected to occur. As the outcrops of thrust-planes usually follow the strike, they are sometimes hard to detect unless they be on a grand scale. But if the observer has been able to make out the general geological structure, and has ascertained that the schistose rocks show a more or less definite succession, careful mapping will reveal all the reversed faults of any importance. Frequently, indeed, these give rise to prominent features at the surface, following as they do some determinate direction athwart the face of mountain slopes, where they simulate the appearance of horizontal or inclined bedding-planes. Thrust-planes are usually rendered conspicuous by erosion. Naturally, they often bring into juxtaposition rocks of very different kinds—on one side, it may be, massive and relatively durable rocks ; on the other side, more readily disintegrated and degraded materials. Not infrequently, therefore, thrust-planes are laid bare by the removal of the softer rocks from the inclined surface of harder rocks upon which they rest. Or, in cases where a gently inclined thrust-plane has brought harder or more durable rocks to rest upon less resistant rocks, an escarpment may be developed by erosion, the geological structure producing the same effect as the intercalation of a relatively "hard" bed in a series of "softer" strata. Occasionally, running water has hollowed out deep gullies and ravines along the outcrops of thrust-planes (Plate XLII.). The presence of a considerable thrust-plane is often further revealed by the crushed and brecciated appearance of the immediately adjacent rocks. So shattered may the rocks be, that the line of movement often resembles the outcrop of a breccia. Still more notable are the evidences of metamorphism induced by such great rock-displacements. Clastic rocks, for example, may be rendered crystalline and schistose, the foliation extending upwards for some little distance above the plane of rock-movement. Massive crystalline eruptive rocks may, in like manner, be crushed and foliated, while ancient gneissose and schistose rocks become similarly modified, new planes of foliation being developed, which may cross the older foliation at any angle. It is particularly noteworthy that the younger foliation always coincides in direction with the plane of rock-movement.

The system of thrust-planes traversing schistose and other rocks in a region of highly complicated structure, is often cut across by one or more systems of normal faults, which shift the thrust-planes just as if they were outcrops. Such faults, therefore, can be detected and followed in the usual way.

Archæan Rocks.—If it be often a hard matter to unravel the structure of a region of highly metamorphosed rocks, it is still more difficult to map out the various complicated and puzzling phenomena presented by the ancient coarsely banded gneissose rocks that seem to form the foundation-stones upon which the oldest sedimentary strata of the globe have been laid down. Hitherto, all attempts to work out the structure and succession of the "Archæan complex," as developed in particular regions, have been more or less unsuccessful. Now and again, what may at first appear to be a series of distinctive kinds of gneiss, alternating the one with the other, seems to suggest a possible chronological succession. But this apparent order rarely continues for any distance. Frequently, one of the gneissic bands will break across another—while the evidence of extreme deformation is everywhere conspicuous. The belief is gaining ground that these ancient rocks are probably for the most part of deep-seated igneous origin—comparable to those batholiths of granite, etc., with their associated sheets, dykes, and veins, which have given rise to the phenomena of contact metamorphism. For sheets of coarsely banded gneiss not only cut across similar sheets of gneiss and beds of what seem to be metamorphosed sedimentary rocks, but ever and anon the gneisses lose their banded structure and graduate into amorphous granitoid masses. Since the time or times of their extrusion, however, all these igneous rocks have been subject to repeated deformation, and dynamo-metamorphism has modified them more or less profoundly.

Although the rocks in question are usually grouped under the general term "Archæan," it is by no means certain that they all belong to early pre-Cambrian times. It is quite possible that, in some cases, they may represent metamorphosed sediments of early Palæozoic age, pierced in all directions by masses and sheets of intrusive eruptives. It is obvious, indeed, that unless they are immediately overlaid by rocks of Cambrian age, their pre-Cambrian origin cannot be demonstrated. Nevertheless, the general similarity of the rocks of the so-called "Archæan complex" all the world over, is suggestive. But the mapping of these old gneissoid rocks, and the interpretation of their evidence, are beyond the resources of the beginner. Not without much patient and skilful work in the field, and prolonged investigation in the laboratory, will the Archæan rocks give up their secret.

CHAPTER XX

GEOLOGICAL SURVEYING—*continued*

Mapping of Unconsolidated Tertiary Deposits, and of Glacial and Fluvio-glacial Accumulations—Boulder-clay; Roches Moutonnées; Terminal Moraines, etc. Raised Beaches. Lacustrine and Fluviatile Deposits. Peat.

Superficial Accumulations.—In this and other countries the "solid" rocks are often concealed under sheets of unconsolidated materials, as gravel, sand, loam, clay, etc. Sometimes these superficial accumulations are confined to valleys and depressions, or they may mantle the entire surface of broad, low-lying lands. They are of very various origin—marine, fluviatile, lacustrine, terrestrial—some dating back to early Tertiary times, while others belong to later periods, and many are still in process of formation.

The TERTIARY deposits of this country, owing to their generally unconsolidated condition, their inconsiderable thickness, and limited extent, may be looked upon as "superficial accumulations." They are chiefly marine, and practically confined to circumscribed areas in the south-east and south of England. On the continent, however, they cover much more extensive areas—in some of which the deposits are essentially of marine origin, while in other regions they are freshwater, or may consist of an alternation of marine and freshwater accumulations. In North Germany, Belgium, France, and England, the beds are arranged in approximately horizontal positions—the marine and fluvio-marine deposits occurring for the most part in maritime districts, and seldom reaching more than a few hundred feet above the sea. The deposits vary much in character—in some places consisting largely of clay or marl, in other places of sand or gravel.

These old sedimentary formations, since the time of their elevation, have been subjected to very considerable erosion, but, owing to their generally unconsolidated character they are not distinguished by any very prominent surface features —but form, for the most part, gently undulating low grounds and plains.* The mapping of such accumulations is attended with some difficulty—it being often hard to trace the outcrops. This is due, in the first place, to the fact that upon slopes the junction-lines are obscured by the washing down of materials from above—the outcrops of lower beds being often entirely concealed under sand, loam, etc., derived from overlying strata. Geologists mapping in such regions occasionally employ a gouge-like spud, which might be described as a kind of exaggerated "cheese-taster," for the purpose of ascertaining the position of the concealed outcrops as accurately as possible. The annexed diagram will serve to illustrate the *modus operandi* (Fig. 120). The surface from *x* to *b* shows nothing but sand, we shall suppose, while between *a* and *x* clay obviously immediately underlies the soil. The observer having reason to believe that the sand at *x* and for some

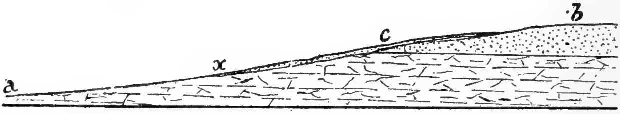


FIG. 120.—CONCEALMENT OF OUTCROP BY SURFACE WASH.
Clay (*a*) overlaid by sand (*b*).

---

* The Tertiary deposits which in England and the low grounds of Middle Europe generally are usually unconsolidated and not much disturbed—spreading as sheets of greater or less thickness over Mesozoic and older rocks—are represented in Southern Europe by much more massive strata—the older portions of which enter largely into the framework of the Pyrenees, the Alps, the Apennines, etc. It would be an abuse of terms to speak of these deposits as "superficial formations." Even in this country, where the corresponding deposits are of slight thickness and more or less unconsolidated, they are, nevertheless, not included by geologists amongst "superficial formations"—this term being restricted to post-Tertiary and recent accumulations alone. From the point of view, however, of the field geologist, all loose and unconsolidated beds of gravel, sand, clay, loam, etc., may be looked upon as superficial accumulations.

distance up the slope is not *in situ* but *remanié*, forces his instrument at intervals down through the sand, until he reaches a place where his borer no longer touches the clay. Unless the amount of sand carried down the slope be very great, it is obvious that the observer can by such means attain a line for his outcrop which cannot be far from the truth.

In low-lying regions of Tertiary deposits, clear natural sections are of infrequent occurrence—the best exposures being met with along sea-coasts, and in recent artificial cuttings and excavations. Frequently, indeed, the geologist is largely beholden to the records of deep well-borings, etc., for information with regard to the succession of the strata, and the probable position of the outcrops. Many hints he will doubtless derive from a careful study of the various soils and the character of the vegetation, and even from the form of the ground. Gravel, for example, being a highly porous deposit rapidly absorbs rain, and is, therefore, less liable to be washed down and trenched by running water, while impervious clay, on the other hand, is readily attacked superficially. The former deposit, therefore, will often tend to form dry lands with a gentle or more rapidly undulating surface. Thick sands, in like manner, will give rise to somewhat similar dry rolling ground; while clays may form low plains or higher tracts trenched in all directions by running water. But in countries which, like our own, have been long under cultivation, the soils of a Tertiary district are often so transformed that it is hard to tell from them what the precise nature of the subjacent deposits may be. For the same reason, plant-associations in such areas cannot always be trusted as guides by the geological surveyor. Such difficulties, however, are only likely to happen when the geologist is dealing with the outcrops of relatively thin accumulations—when, on the other hand, a stratum or series is thick and covers wide areas, the nature of the soil and the character of the vegetation will help the observer to trace its extent with more or less confidence. Speaking in general terms, we may say that the mapping of unconsolidated Tertiary deposits is carried on in much the same way as the tracing of consolidated sedimentary strata. Now and again they are gently folded, and assume a basin-shaped arrangement, and when such is the case the outcrops are not so hard to trace.

GLACIAL AND FLUVIO-GLACIAL ACCUMULATIONS.—The deposits included under this head are widely distributed in this country and in corresponding latitudes of the Continent and North America. They cover extensive areas in our lowlands—occupying valleys and sweeping over intermediate tracts, so as largely to conceal the underlying solid rocks. In our mountainous districts they are mostly restricted to the valleys, but often extend upwards to considerable heights upon the mountains themselves. It would be quite beyond the limits of this work to attempt any detailed description and classification of these accumulations. Attention is, therefore, limited to some of the salient phenomena presented by the more notable of the deposits in question.

(a) *Boulder-clay or Till.*—This is an unstratified or amorphous mass, the essential lithological characters of which have already been given (see p. 63). One of its most striking peculiarities are the stones and boulders which it contains. These are almost invariably fresh, unweathered, and generally blunted and subangular in shape—often showing smoothed, polished, and striated faces. The beginner should note especially the character of the striation and its relation to the shape, size, and species of the stones. Usually, stones which are longer than broad are most distinctly striated lengthways, while those which are as broad as they are long are striated equally in all directions; very large blocks are often smoothed on one side only, while smaller boulders and stones are commonly smoothed all over; again, compact fine-grained rocks, such as limestones, shale, ironstone, felsite, etc., have usually received a better polish than coarse-grained grits, sandstones, etc. The observer should be on the outlook for any traces of arrangement of the stones and boulders. Occasionally, lines of small and large boulders may be seen traversing the face of a cutting in boulder-clay—the boulders not infrequently lying lengthways. Sometimes the upper surfaces of such "boulder-pavements," as they are termed, are distinctly striated in one common direction. The student should also subject the gritty clay itself to a close examination. A portion should be taken home and thoroughly dried and crumbled down, when the shape and nature of the larger fragments can be studied with the help of a lens. These will be found to be simply minute boulders, angular, subangular, and often striated, and quite unweathered. The "clay" may be still further reduced by shaking it in water and passing it through a sieve. By using sieves of various degrees of fineness, all the gritty particles above a certain size may be sifted out, and only an extremely fine-grained residue be left. The grit, examined microscopically, is found to resemble in every respect, save size, the small fragments which the student may have determined with the aid of his pocket-lens. They all alike consist of fresh, unweathered mineral matter. The residue which is not separated by the finest meshed sieve may be reduced by shaking it in water and allowing it to settle. From the turbid water a sediment is gradually thrown down. The water which still remains clouded can then be decanted and allowed to stand until it clears. In this way we obtain a still finer grained mechanical precipitate. These sediments are of precisely the same character as the gritty materials separated by the sieve—they are fresh and unweathered, being composed of what may be termed "rock-flour," the chief constituent of which is powdered quartz. It is this "rock-flour" that forms the major portion of the so-called boulder-*clay*—the proportion of true clay throughout the mass appearing to be relatively insignificant. Indeed, according to Professor Crosby, "till in its natural condition is often less than one-tenth and rarely more than one-eighth pure clay."

Boulder-clay is believed to be the bottom- or ground-moraine of massive glaciers or ice-sheets—and to have been formed by the crushing and grinding action of ice in motion. Formed and accumulated under these conditions, we can readily understand why it should consist essentially of fresh, unweathered rock-materials. But it is beyond the purpose of these notes to give any particular account of this remarkable formation. It may, however, be of service to the field-observer to indicate certain points which ought to be noted when he begins to map in a till-covered region. First, then, the configuration of the surface should be considered. Sometimes the ground in such a region is devoid of any prominent feature, rising and falling in long, gentle undulations, that may not trend in any particular direction. In other cases, the surface is more diversified, and may show a pronounced "corduroy" or wrinkled configuration—being marked by a series of longer and shorter parallel and often interosculating banks with intervening hollows. The trend of these *drums*, or *drumlins* as they are called, should be carefully noted. In most cases the banks in question appear to be original, *i.e.* they are forms assumed by the boulder-clay while it was being accumulated. Occasionally, however, they are simply the result of the unequal erosion of a gently undulating or plain-like surface of boulder-clay.

The colour of the till and the nature of its included stones and boulders should be noted. The colour will usually be found to correspond with that of the predominant rock or rocks of a district—it is therefore *local.* The most abundant rock-fragments in the till are also generally local, but commingled with these many others of more distant derivation are sure to occur. The observer should take percentages of the different kinds of rock, and endeavour to ascertain their several sources. If he be a beginner he will naturally be at fault, but a good geological map of the country will afford him some help, and he may obtain more by examining the rock-collections in public museums. Should he be able to determine the source of many of the stones which are "strangers," this will give him a strong hint as to the general direction followed by the old *mer de glace.*

Lenticular layers and sometimes thicker series of unfossiliferous gravel, sand, and laminated clay, may occur underneath, and are still more frequently included in boulder-clay. Such deposits are often more or less confused and disturbed. They obviously point to the action of subglacial water. The boulder-clay that immediately underlies them will be found quite fresh and unaltered, showing that it has never been exposed to the oxidising influence of the atmosphere. Now and again, however, stratified deposits of gravel, sand, loam, marl, peat, etc., are met with resting upon and covered by boulder-clay. The boulder-clay underneath such beds is almost invariably discoloured for some distance downwards, thus showing that it must for some time have been

Glacially-striated Surface of Slates, Kilchiaran, Islay.

Photo by H.M. Geological Survey.

acted upon by the atmosphere and surface water. The stratified deposits in question have often yielded relics of an old land-surface, and are thus evidence that the formation of boulder-clay was an interrupted and not a continuous process. The same inference may be drawn from the occurrence of marine fossiliferous deposits included in till.

The relation of the boulder-clay to the immediately subjacent rocks is deserving of study. The latter are sometimes so broken, jumbled, and confused, that it is hard to say where the shattered and disturbed rock ends and boulder-clay begins. The student should note whether the slabs and reefs of rock have been bent over or wedged out of their beds, and the direction in which they have moved should be ascertained. Instead of being broken and jumbled, the subjacent rocks may show a smoothed, polished, and striated surface. The compass bearing of the striæ should always be taken, as this indicates precisely the direction of ice-flow at the point of observation. It is possible that the beginner may at first have some difficulty in distinguishing between a glacially striated surface (Plate LII.) and slickensides (Plate XXXVI.). The latter, however, are usually confined to flat or even surfaces, and are frequently glazed with mineral matter—the scratches, moreover, are strictly parallel. It will be noted further that when a slickensided surface shows any depressions these are not striated. Glacial striæ, on the other hand, may occur on flat, convex, concave, or rapidly undulating surfaces. The smoothing and polishing is not confined to the protuberances upon a rock-surface, but every little dimple and depression is equally dressed. Although roughly parallel, glacial striæ are yet not so straight as slickensides, but often cross each other at acute angles. Frequently, indeed, they may be seen curving gently round the sides of projecting knobs, as if these had caused some slight deviation of the ice-flow. The scratches may be as fine as if drawn by an engraver's needle, or they may be coarse, jagged ruts; and between these extremes all gradations occur, and may be seen side by side on the same rock-face.

Roches moutonnées.—Dressed rock-surfaces occur not only underneath boulder-clay, but on exposed hill-slopes and rocky elevations, from which the boulder-clay has been stripped by denudation, and in many places also where probably no boulder-clay was ever deposited. The observer should take particular note of the configuration of the hills and mountains of a glaciated region (see Plate LIII.). Land which has been subjected to extreme glaciation generally shows flowing contours. Projecting prominences and crags are smoothed and rounded off on the side that faced the ice-flow; while the opposite side, protected by its position, may retain its original roughness. The smoothed face is termed the *Stoss-seite*, and the non-glaciated face, the *Lee-seite*. Whole mountain-slopes may exhibit a rudely mammilated surface, the rounded rock-surfaces being often striated. Sometimes the ice-markings are fresh and readily recognisable; at other times they have almost vanished—the mere "ghosts of scratches." Even when they have disappeared, however, the mammilated outlines of the rock-masses are cogent evidence of the former presence of glacier-ice. These rounded hummocks or *roches moutonnées*, as they are called, generally indicate clearly enough the direction of ice-flow. In the case of abrupt crags and tors the stoss-seite is usually steep, while the lee-seite assumes the form of a long sloping ridge. This phenomenon is known as *crag-and-tail*. Sometimes the tail is composed entirely of glacial-detritus (boulder-clay, gravel, etc.). More frequently (especially when the crag is very prominent and of considerable dimensions) the "tail" consists largely of solid rock, usually covered with a less or greater thickness of boulder-clay, etc.

Terminal Moraines: Perched Blocks, etc.—In many of our mountain valleys, angular blocks and earthy débris are sprinkled more or less abundantly over the ground, up to very considerable elevations. In the bottoms of the valleys, knobby ridges, mounds, and hillocks, composed of the same materials, are of common occurrence. The character of the deposits, the peculiar shape of the hillocks, etc., and their position, are comparable in all respects to similar phenomena occurring in the glacier-valleys of alpine regions. There can be no doubt that they are the *terminal moraines* of extinct glaciers. Low ridges or banks, or lines of morainic débris running along the mountain-slopes of many highland valleys, correspond to the *lateral moraines* of existing glaciers. *Perched*

PLATE LIII.

GLACIATED ROCK-SURFACES, ACHNASHELLACH, ROSS-SHIRE.

Photo by H.M. Geological Survey.

[*To face page* 314.

blocks are erratics which have been carried by the ancient glaciers, and successively stranded as the great ice-flows melted away.

Sheets and Mounds of Gravel and Sand.—Throughout wide areas, boulder-clay is often more or less deeply buried under gravel and sand. These deposits may assume the form of extensive sheets with a gently undulating surface; or they may occur as long curving and irregularly winding ridges; or as tumultuous groups of closely associated mounds, hummocks, and ridges, known as *kames.* Sometimes the accumulations consist principally of fine sand—often diagonally bedded—or of interbedded sand and laminated clay. In other places, sand and gravel are equally prominent, while elsewhere coarse shingle and boulders are most abundant. At rarer intervals a mound or ridge may be composed of rude morainic débris—a rubble of angular blocks and rock-rubbish.

FIG 121.—COARSE GRAVEL AND SHINGLE, SHOWING IMBRICATED STRUCTURE.

The arrow indicates the direction of the current.

It is obvious that deposits so heterogeneous could not all have been formed in quite the same way; and it would be out of place here to discuss the various views which have been entertained as to their origin. The general belief, however, is that all the deposits in question were accumulated while the old icy covering of the land was gradually melting away. The observer will note that the long winding ridges (known as *eskers*) are composed chiefly of gravel—often very coarse—with more or less numerous boulders. They have obviously been laid down by torrential water—and when good sections across an esker are exposed, the stones sometimes show that imbricated arrangement which one may often observe amongst the stones and coarse shingle of streams and rivers (Fig. 121). Many geologists incline to the belief that these eskers mark the sites of subglacial torrents by which the great *mers de glace* were tunnelled, especially during the period of their final dissolution. In the low-lying parts of the country, many wide sheets of sand and gravel seem also to have been accumulated underneath the melting ice-flows, for they are often closely associated with eskers. In other cases, however, they may have been distributed over the exposed surface of the low lands by water escaping from the gradually disappearing snow-fields and decaying glaciers of adjacent high grounds.

In hilly and mountainous tracts, narrow and broad terraces and considerable plateaus of gravel, sand, and clay obviously mark the sites of ancient glacier-lakes. Such are the Parallel Roads of Glenroy, the wide sand-plains covering the watershed between the rivers Avon and Irvine in the neighbourhood of Loudoun Hill, and many similar terraces and flats occurring in the Northern Highlands and Southern Uplands. Even the hill-slopes overlooking the broad lowland tracts of Scotland now and again show strong evidence of the former presence of temporary glacial lakes, which appear to have come into existence after the hills in question had been divested of their icy covering, and while the adjacent lowlands were still thickly mantled by the gradually decaying *mer de glace.*

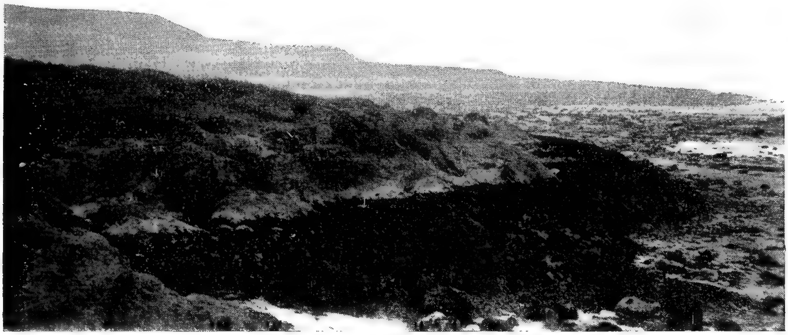
There seems also to be little doubt that those tumultuous assemblages of hummocks, cones, and ridges known as kames, are of the nature of gravelly moraines, deposited in front of giant glaciers or district ice-sheets. Often associated with them are wide sheets of sand, loam, and clay, which spread out over the low-lying tracts, upon the borders of which the gravelly moraines have been accumulated. Perhaps one of the best areas for the study of these phenomena is the great valley of Strathmore.

Although the external form of glacial and fluvio-glacial deposits is often original, yet occasionally widespread sheets of sand, gravel, etc., have been so cut up by subsequent epigene action as to present a more or less rapidly undulating or corrugated surface. When this is the case, such a denuded plain now and then simulates the appearance of "drums" and "kames." Usually, however, the observer is not likely to mistake a surface of erosion for one of accumulation. If the deposits consist of evenly bedded gravel, sand, etc., the subsequent origin of the mounds and banks will be disclosed by the manner in which the horizontal beds are truncated by the slopes of the ground. It is more difficult to differentiate between a true "drum" or "drumlin"—that is, a bank or ridge of boulder-clay due to glacial accumulation, and banks of the same material which have resulted from the irregular erosion of a thick continuous sheet. If the banks do not trend in the same direction as the *roches moutonnées* and striæ of a district, then they are not true drumlins. Should their trend appear to coincide generally with that of glaciation, the whole modelling of the surface must be studied before we come to the conclusion that the banks are original structures. If they have been carved out of a sheet of boulder-clay by running water, evidence of this should be found in the arrangement of the intervening hollows, which will be grouped much in the same way as the feeders and tributaries of a stream. In other words, the banks and ridges of the district will not be arranged throughout in parallel positions, but will fan-out as they are followed in a direction opposite to that of the water-flow. Moreover, the existing brooks and their feeders, or, should these have disappeared, the evidence of their former presence afforded by flats and terraces of alluvial deposits occupying the hollows, would be sufficient to convince us that the banks or ridges were not true drumlins, but secondary structures. It is to be noted, however, that true drumlins are of two kinds—while some have been accumulated as such underneath the old ice-sheets, others would appear to be merely the remnants of widespread sheets of boulder-clay which have been exposed to subsequent glacial erosion. In Galloway, for example, the low grounds extending outwards from the mountains were originally deeply covered with extensive sheets of boulder-clay, by the *mer de glace* that formerly overflowed all that region. Long after the disappearance of that ice-sheet, great glaciers streamed out from the mountain-valleys for some little distance, and trenched and furrowed the older boulder-clay—thus forming a series of secondary drumlins.

RAISED BEACHES.—These are flats and terraces occurring at various levels above the sea (see Plate LIV. 1). They may consist of ordinary beach materials—gravel and sand with rolled and broken sea-shells, etc. Along the margins of estuaries they often form wide flats, composed for the most part of finer materials—sand, clay, loam, silt, etc. On our more exposed sea-coasts the raised beach-lines are frequently mere platforms and ledges, which have been sawn out of the solid rocks by the sea. Many old beaches are backed by cliffs, at the base of which sea-worn caves not infrequently appear. In Scotland there are three "ancient sea-margins" which are particularly noteworthy. They occur at heights of 100 feet, 50 feet, and 25 feet respectively. The highest is the oldest, and is best developed in the basins of the Forth, the Clyde, and the Tay. It is composed largely of laminated brick-clay, together with fine sand. Scattered through these deposits occasional stones occur, and now and again large erratics are even common. The beds not infrequently yield Arctic species of shells, etc. The observer will find it interesting to follow the 100 feet beach or terrace up the valleys until it merges into terraces of ordinary fluviatile shingle and gravel. When the latter are traced further inland into the mountains, they will eventually be found to interosculate with fluvio-glacial gravels and terminal moraines.

The two lower terraces are of later date, but their geological history has not yet been so fully worked out as it deserves to be.

LACUSTRINE AND FLUVIATILE DEPOSITS.—The sites of old lakes are readily detected. They invariably occur, as might have been expected, in hollows and depressions, and usually form level meadow-lands. Their margins, as a rule, are well defined. The observer should never miss the opportunity of examining any cuttings in which the old lacustrine deposits are exposed. Very often the immediate surface is occupied by peat of less or greater thickness—or several layers of peat may be interstratified with sand or silt. The peat may consist entirely of plants which still grow in the neighbourhood. Now and again, however, Arctic plants have been detected in the basal part of the peat or in the immediately underlying silt or clay. Sometimes, also, traces of Arctic animal life are met with in the same deposits. This proves that some of



1. Raised Beaches, near Elie, Fife.

Photo by Dr Laurie.

2. Moss near Yellow Tomach, Merrick Hills.

Photo by Mr F. J. Lewis.

[*To face page* 318.

these ancient lakes date back to the glacial period. Even those lacustrine deposits which are entirely of post-glacial age, have often yielded interesting fossils—amongst which may be mentioned remains of the ancient types of oxen (*Bos primigenius*, *B. longifrons*), the great Irish deer, wolf, beaver, etc., not to mention relics of prehistoric man. Freshwater shells also frequently occur, forming beds of shell-marl.

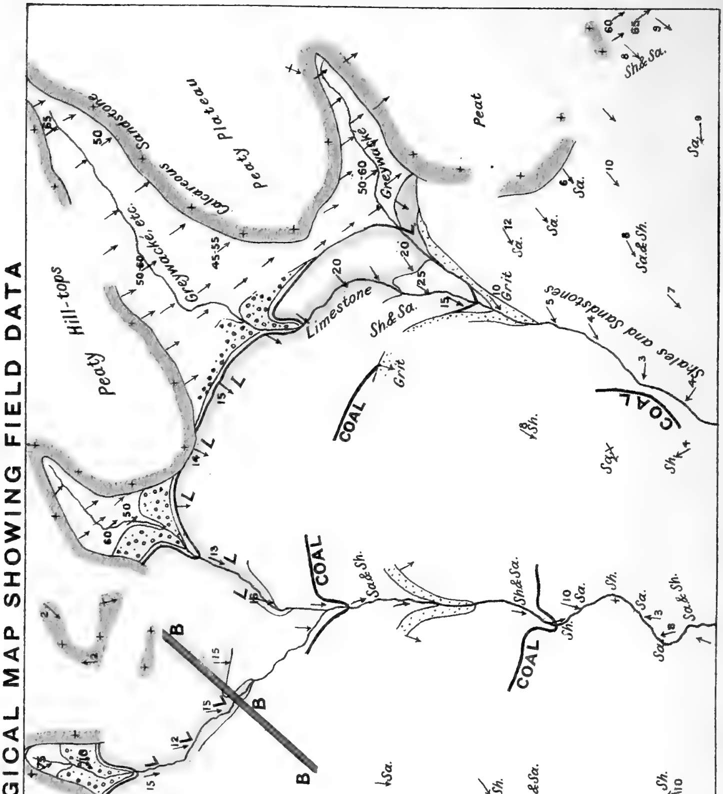
Very few broad river-valleys fail to show old terraces of gravel, sand, etc., occurring at various levels above the present streams. These mark levels at which the rivers formerly flowed. Terraces of this kind are best developed in valleys which have been more or less abundantly clothed with glacial and fluvio-glacial deposits: or in regions where the rocks have yielded not less readily to fluviatile erosion. In a country like Scotland, where the rocks are all relatively "hard," old river-terraces may be said never to occur outside of preglacial valleys. So long as our rivers follow their preglacial courses, those terraces are almost invariably in evidence—the rivers making their way through broad open valleys. No sooner, however, does a stream leave its preglacial course to cut its way through the older rocks, than the whole character of the valley changes. The stream no longer flows through a wide terrace-fringed valley, but through a relatively narrow ravine.

PEAT.—Reference has been made to the occurrence of peat in old lacustrine depressions. But, as everyone knows, peat often covers wide areas of rolling low ground and high plateau, and even swathes relatively steep mountain slopes. In some regions, indeed, it is found capping flat hill-tops. There is no difficulty in mapping peat-bogs, but a careful study of their phenomena has still to be made. It is well known that many peat-bogs cover and conceal the stumps and stools of trees which are rooted in an ancient soil, and obviously, therefore, grew *in situ* (see Plate LIV. 2). Not only so, but deep cuttings in certain peat-bogs have revealed the presence of one or more such old "forest-beds" occurring one above another in the peat itself. Scandinavian, Danish, and German observers have detected in the peat-bogs of Northern Europe similar phenomena, and have gathered much additional botanical evidence of varying climatic conditions. Until recently few attempts had been made by competent botanists to subject the peat-bogs of this country to a like careful examination. Geologists specially interested in the later chapters of the stony record have for a long time believed that a rich harvest of results would yet be reaped in this promising field of inquiry. The purely geological evidence seemed to lead to the conclusion that the peat-bogs with their associated "forest-beds" belonged to a period during which several well-marked alternations of climate took place—the peat being the product of wet and cold conditions, while the "forest-beds" indicated relatively dry and temperate conditions. The results recently obtained by Mr F. J. Lewis, in his botanical investigations into the composition and structure of our peat-bogs, have abundantly confirmed that conclusion. He has discovered distinct zones of Arctic plants in the peat of lowlands and highlands alike, and thus we can no longer doubt that the closing stages of the geological history of our islands were characterised by alternations of cold and temperate climatic conditions.*

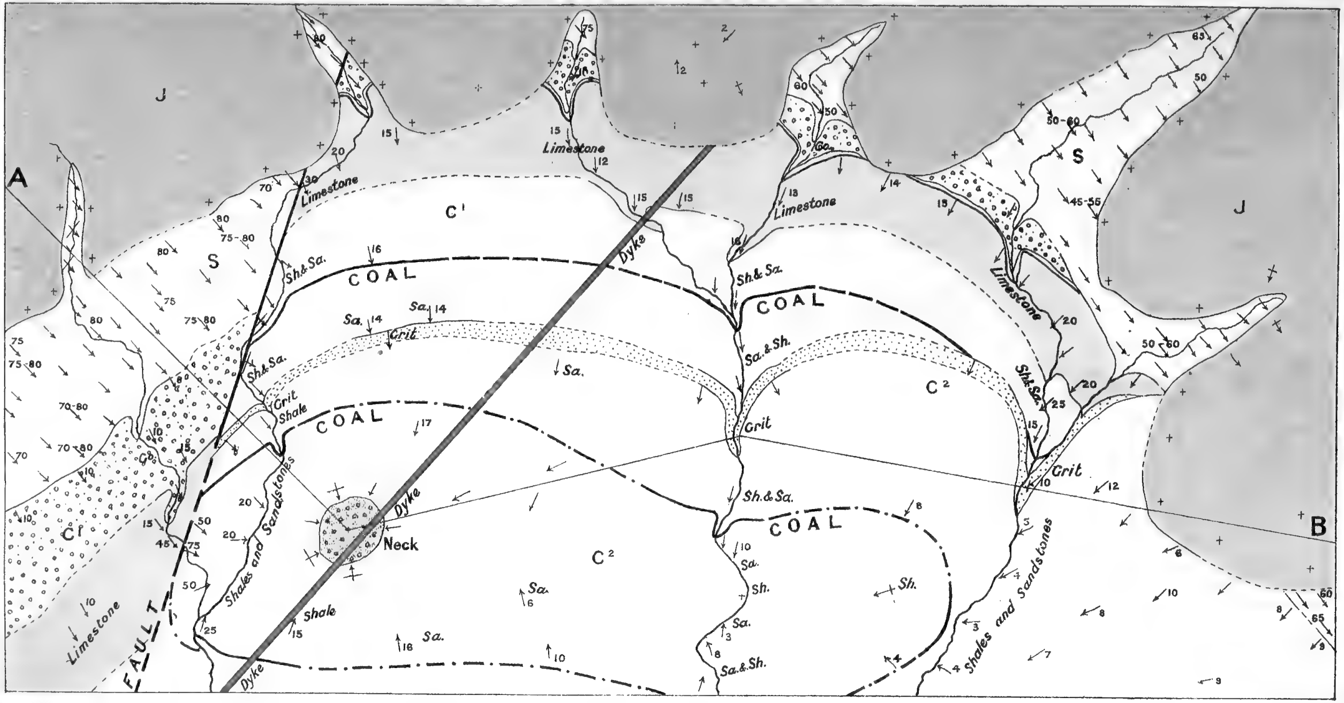
---

* For a general account of Mr Lewis's investigations see *Science Progress*, Vol. II., p. 307.

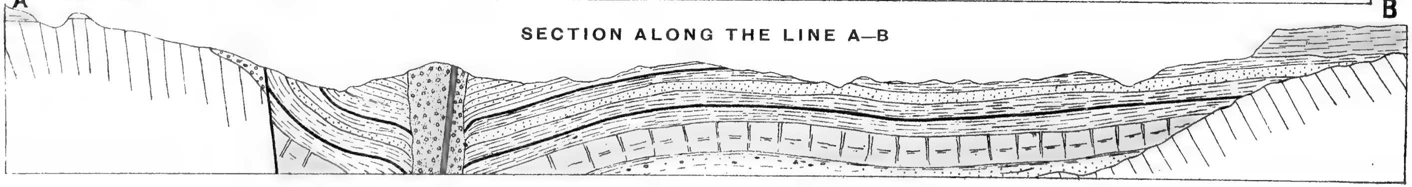
SKELETON GEOLOGICAL MAP SHOWING FIELD DATA



COMPLETED GEOLOGICAL MAP



SECTION ALONG THE LINE A—B



CHAPTER XXI

GEOLOGICAL MAPS AND SECTIONS

Geological Maps and Explanatory Memoirs. Geological Sections—Horizontal or Profile Sections should show both the Form of the Ground and the Geological Structure; Direction in which such Sections should be drawn; Method of plotting a Section on a True Scale. Vertical Sections.

Geological Maps and Explanatory Memoirs.—The accompanying maps (Plates LV., LVI.) will serve to illustrate the method of tracing geological lines, some account of which has been given in the two preceding chapters. In Plate LV. only the actual rock-exposures seen by the geologist are represented. These are indicated by the arrows and continuous lines, the patches of colour showing the extent of the areas where rocks come to the surface. Plate LVI. represents the same region with the several boundary-lines, etc., completed. The direct and indirect evidence which guides the observer in carrying outcrops, faults, etc., from one point to another, must no doubt be of unequal value. In some places it may be so convincing that one may almost feel justified in representing outcrops, etc., by means of continuous lines, while in other places it may be so slight that the boundaries laid down upon the map can be only an approximation to the truth, and should, therefore, be indicated by dotted or interrupted lines. A glance at the maps will show that the geological structure of the region represented is so devoid of complexity and the evidence so full, that the observer could hardly go far astray in carrying lines across such a country. The maps are merely diagrams, however, designed to bring into one view certain leading structures and the method of tracing these, and therefore it must not be inferred that outcrops can be always so satisfactorily followed. Sometimes, indeed, the ground-rocks are so obscured over wide areas, by superjacent glacial or alluvial accumulations, that the general geological structure can only be surmised, and the following of outcrops becomes impossible. At other times the region may be so abundantly faulted that no cautious geologist would venture to continue an outcrop beyond the point where the rock itself could be proved to exist. Occasionally, however, in the case of valuable rocks and minerals (coal, ironstone, etc.), the observer, desirous of helping the mining engineer in his search for such seams, might be justified in indicating by means of interrupted lines the general course which he thought the outcrops were likely to take. But in doing so, he would be careful to note upon the map or in his description that the outcrops were largely conjectural, and therefore not to be implicitly trusted.

Three geological systems are represented on the diagram-map—Silurian (S), Carboniferous (C), and Jurassic (J). Each of these systems, we shall suppose, has yielded to the investigator its assemblage of type-fossils. It will be observed, however, that, even in the absence of fossils, the geologist could have had no difficulty in detecting the presence of three distinct series of strata, and in ascertaining the order of their succession. The rock-exposures are so numerous that they at once reveal the geological structure. The series marked J, for example, rests with a strong unconformity upon the series C; the latter bearing in like manner a similar relation to the series S. Another unconformity of less importance occurs in the Carboniferous series, where the upper group (C^2) is represented as gradually stealing across the outcrops of the lower group (C^1)—the structure, indeed, is a combination of overlap and unconformity. The accompanying section is taken along the line A—B, and gives a view of the general geological structure.

In his monograph or explanatory memoir of such a region, the geologist would probably begin by sketching its physical features, after which he would proceed to give some account of the general distribution of the several systems, and their relation to one another. Next would follow a particular description of each, beginning with the oldest.

The several faults and the eruptive rocks would likewise call for ample notice. In short, every detail of scientific interest and economic importance would be duly set forth in its proper place. But if his monograph were written for experts only, the geologist would necessarily leave much unsaid, knowing that his readers might be relied upon to fill in outlines and to draw obvious inferences for themselves. He might, indeed, not infrequently content himself with a bare narration of facts, and leave these and his map to tell their own tale. Interpretations and explanations would only be called for in cases where the evidence was incomplete or not quite clear.

The beginner, however, who essays to work out the geological structure of a district, would do well to ponder over the evidence as it grows, and endeavour to realise the particular conditions under which the various rocks and rock-structures originated. His object is not only to make a correct geological map and to present a detailed report of what he has observed, but to picture to himself as clearly as he can the succession of changes which have taken place in the region surveyed. If he is dealing with sedimentary strata, he must be on the alert to notice every variation in the character of the deposits, every fact that would seem to throw light upon the conditions that obtained at the time the strata were being accumulated. As the evidence furnished by fossils is always most important, he will be on the constant outlook for these. Only by keeping each kind of evidence—that of the fossils and that of the rocks themselves—constantly in view, can we hope to read geological history aright. If we have previously made ourselves well acquainted with the nature and mode of formation of sediments now being laid down in lakes, estuaries, and seas, and have acquired a sufficient knowledge of the various ways in which organic remains come to be entombed, we shall be prepared to give a good account of any series of sedimentary strata we may encounter. Most of the fossils we may detect will in all likelihood belong to well-known genera—probably most of the species themselves will already have been recognised by palæontologists—so that with the combined evidence of rocks and fossils the observer will be in a position to realise the conditions under which the fossil-bearing beds were laid down. He should be able, in short, to summon up a picture of the past. The more fully he has stored his mind with a knowledge of geological changes now in operation, and the more consistently he applies this knowledge towards the interpretation of the stony record, the better investigator must he become, and the more clearly and vividly will the dead past live again for him. It is this clothing of the dry bones with flesh, this reconstruction of long-vanished lands and seas, this repeopling of the world with types of life that have passed away for ever, this gradual unfolding of earth-history—it is this, perhaps more than all else, that fascinates the earnest student of geology. The "scientific imagination," therefore, ought from the first to be stimulated by every observation one makes. Even within the limits of a single quarry one may often meet with evidence from which to reconstruct quite a number of interesting geological episodes. Small and unimportant the phenomena may seem to be, but the care bestowed on their interpretation will not be lost. Gradually, as we continue our investigations, our eyesight becomes sharpened; we not only see better than we did when we commenced, but are able eventually to take a wider outlook, and to piece together bits of evidence which at first might have appeared isolated and unconnected. From all which it is obvious that the observer who cultivates the scientific imagination is likely to produce a better and more reliable geological map than the cartographer who declines to look beyond the obvious facts. The former is on the way to become a shrewd generaliser and discoverer; the most the latter can hope to do is to provide materials for others with a wider outlook to work up and interpret.

Geological Sections.—When the geologist has completed his map, he usually prepares one or more horizontal or profile sections to illustrate the general structure of the region. With an accurately constructed map, sections might often be dispensed with, since anyone who can read such a map could draw sections across it in any direction. Few maps, however, are large enough to show all the needful data, and the smaller and more generalised the map is, the more necessary do explanatory sections become. Two kinds of sections are constructed, namely, *Horizontal* or *Profile* and *Vertical*, the former being designed to show the form of the ground and the geological structure of the region traversed, while the latter are meant to exhibit in detail merely the vertical succession of the strata.

Horizontal (*Profile*) *Sections.*—If these are to be accurately constructed, they must be drawn upon a true scale—that is, the vertical and horizontal scales must be the same. The young geologist's first attempts at section drawing should therefore be on this true or natural scale. If the vertical scale be exaggerated, it is obvious that the lines which are meant to show the geological structure must be correspondingly distorted. A glance at the two sections (Figs. 122, 123) will serve to make this plain. Fig. 122 is drawn on a natural scale, and therefore exhibits the actual form of the surface, and the true dip of the strata. In Fig. 123 we have the same section, but in this the vertical is three times greater than the horizontal scale—the result being that not only are the surface features grossly exaggerated, but the geological structure is distorted—the inclination of the strata being greatly in excess of the true angle of dip. It is only by carefully plotting our sections to exhibit the actual form of

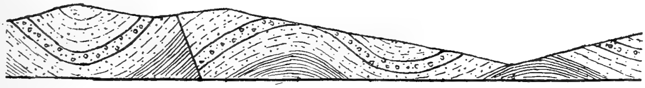


FIG. 122.—SECTION ON A TRUE SCALE—THE HORIZONTAL AND VERTICAL SCALES BEING THE SAME.

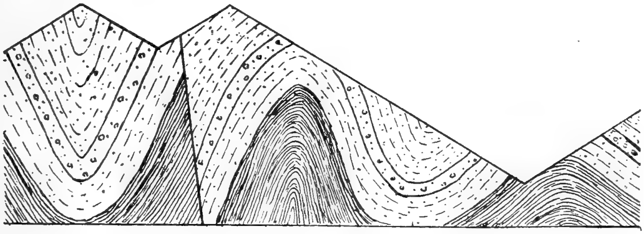


FIG. 123.—SECTION ACROSS SAME AREA AS IN FIG. 122—THE VERTICAL BEING THREE TIMES GREATER THAN THE HORIZONTAL SCALE.

the ground, that we learn to appreciate the intimate relation that obtains between surface features and geological structure. Everyone is prone to exaggerate slopes—even experienced artists frequently do so, especially in the case of mountains—and the young geologist who neglects to train his eye by frequent section drawing on a true scale, is not likely to escape this common failing. The beginner will find it excellent practice to draw topographical (not geological) sections in all directions across some of the hilly tracts represented on the large 6-inch maps of Scotland. He will doubtless be surprised to see how inconspicuous many heights appear when drawn to scale, how relatively gentle are the undulations of the surface even in a mountainous tract. In the same way he will recognise that the deep basins occupied by our larger lakes when seen in their true proportions are mere shallow pans or troughs. Loch Ness, for example, is 780 feet deep, but then it is not less than 22½ miles long, so that the length is 152 times greater than the depth.

Of course it is not always possible to plot geological sections on a true scale. If the region to be illustrated be of great extent, say 100 miles across, it is obvious that we must generalise both the topography and the geology. Even in such cases, however, it is important to indicate as clearly as may be the leading surface features of the region and the relation of these to the geological structure. A similar remark holds good with regard to all sketch-sections. Should the heights and slopes of the land be so inconspicuous as to be barely perceptible when drawn upon a natural scale, it is often necessary to exaggerate them in order to show their relation to the internal structure. The exaggeration, however, should not be so pronounced as to amount to positive distortion.

In running a geological section, care should be taken to draw it as nearly as possible at right angles to the strike. If the strata be inclined in the same direction throughout a district, the section will necessarily follow a straight line. But should the strike vary from point to point, the line of section will be correspondingly sinuous or zig-zag. Reference to Plate LVI. will show how frequently the direction of a section-line must change, when it is desired to bring into one connected view the general geological structure of a whole district. The section in question is a mere diagram, and is therefore not drawn to scale, but it exhibits the leading surface features and their relation to the underground structure.

There is no difficulty in plotting a profile section on a true scale. If the student has laid down his geological lines upon the 6-inch map of the Ordnance Survey, all he has to do is first to draw a line across the map in the direction to be followed by his section. Next, on a separate sheet of paper, he draws a line to represent the sea-level. Upon this datum-line he erects verticals for the heights of the land traversed by his section, which he obtains, of course, from the contours on the map. When the extremities of these lines are connected they give the average form of the ground. If it be desirable to reproduce the surface features in greater detail, the observer may walk over the ground with his section in his hand, and so modify the line as to show the subordinate irregularities that appear between the measured contours. Usually, however, this refinement is not necessary, when the contour lines upon the map succeed each other at intervals of 100 feet or less. At the higher elevations of the land the intervals between the contour-lines increase to as much as 250 ft., and when such is the case the geologist will probably consider it advisable to revisit the ground, in order to make the upper line of his section represent, as closely as may be, the varying configuration of the surface.

Having satisfied himself as to the correctness of this upper line, he then proceeds to insert the dips of the strata, and every detail shown upon his map along the line of section. Probably the section will now and again traverse places where outcrops are not seen, but, the structure of the ground having been carefully worked out, he will usually have no difficulty in filling in these blanks from the evidence supplied by rock-exposures seen elsewhere on the same geological horizon. After all the data referred to have been inserted, the question arises—how far are the dips exposed at the surface to be continued downwards? The depth to which we may carry our lines will naturally depend upon the geological structure. If our section should traverse normal anticlines and synclines, we need have no doubt as to the conduct of the lines below the surface. In the case shown in Fig. 124 the strata between *a* and *b* are obviously symmetrically folded. We, therefore, should be justified in continuing the dips of the synclinal strata downwards for some distance at the same angle as they show at the surface, and then gradually cause the degree of inclination to diminish until the beds should become horizontal in the core of the synclinal trough. If the rock-folds, instead of being "open" as shown in the diagram at *a*, were closely compressed as between *b* and *c*, the curves of synclinal and anticlinal cores would be more or less sharply angular; and in our section we should have to continue the limbs of a syncline downwards for a relatively greater distance before the trough core was reached. In short, when gently inclined strata dip towards each other at approximately the same angle, we may be sure that the inclination of the limbs will rapidly lessen as they approach the trough core, while in the case of steeply inclined and closely compressed unsymmetrical folds, the limbs of a syncline must descend to a relatively greater depth before they meet.

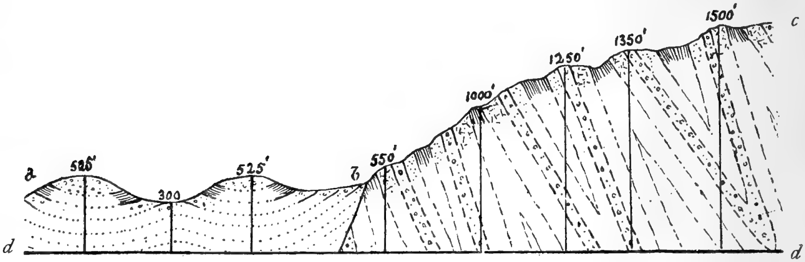


FIG. 124.—DIAGRAM-SECTION.

Vertical lines = heights above datum-line (*d*). Continuous lines = outcrops. Interrupted and dotted lines = inferred direction of strata below the surface.

In regions which have not been topographically surveyed, or the maps of which, if such exist, give very few elevations, the geologist must, of course, do his own levelling, if he desires to plot a section on a true scale. In such a case he may select any line for the base of his section—either the sea-level, the surface of some lake, or the bottom of some valley, etc., or he may prefer to erect his section on some imaginary line drawn at any distance below the surface.

Vertical Sections.—These are sections so drawn as to show all the strata piled up, as it were, in a tall column in their proper order of succession. Where no unconformities occur, the dip of the strata is usually neglected, and the beds are arranged in a horizontal position. As sections of this kind are meant to show in detail the succession of the strata in a coal-field or other area containing beds and seams of economic importance, they are drawn on a large scale—a much larger scale than would be employed in the construction of even the most elaborate profile section. In the case of vertical sections great accuracy is required—the thickness of each individual bed being carefully measured in exposed rock-sections, or obtained from other reliable sources, as from records of the rocks passed through in sinking wells, pits, bore-holes, etc. The Geological Survey publishes sheets of such sections to show the succession of beds encountered in our coal-fields. By comparing the vertical sections illustrating any particular coal-field, we can see at a glance how the same series of strata varies as it passes from one part of the coal-field to another. Similar vertical sections, usually on a much smaller scale, are now and again constructed by geologists for the purpose of comparing the succession of strata met with in one place with that encountered in some other area where rocks of the same age occur. It is, in short, a graphic method of showing how the same formations and systems vary in character as they pass from one region to another.

CHAPTER XXII

ECONOMIC ASPECTS OF GEOLOGICAL STRUCTURE

The Search for Coal—Conditions under which Coal occurs. Trial Borings. The Search for Ores—General Considerations which should guide the Prospector; Nature of the Evidence. Geological Structure and Engineering Operations—Excavations, Tunnels, Foundations.

In preceding chapters dealing with Tectonic or Structural Geology, much that is of interest and importance to engineers and others has been set forth in more or less detail. No attempt, however, has been made to indicate the various ways in which a knowledge of rock-structures may be utilised by mining and civil engineers, architects, and others—for the simple reason that the application of the knowledge in question must be sufficiently evident. In the present chapter, however, it may not be out of place to give a few supplementary notes which could not be well inserted in earlier pages.

The Search for Coal.—In regions the geological structure of which is well known, and good maps of which are available, not much difficulty need be experienced by the mining engineer who can read and interpret geological maps and sections. He may often be at a loss, however, in searching for coal, etc., in a country the geology of which is only imperfectly understood, or even not known. Under such conditions his first care would necessarily be to ascertain the geological age of the sedimentary strata by searching for fossils. Coal occurs in several geological systems. In Britain, workable seams are practically confined to the Carboniferous system, and the same is largely the case in many other regions, both in Europe and North America, In Australia, India, and Southern Africa, and in Virginia and North Carolina, U.S.A., workable coal occurs on higher geological horizons—namely, in late Palæozoic and early Mesozoic strata. Here and there, but only at wide intervals, seams of economic value are also encountered in the younger Mesozoic systems (Jurassic and Cretaceous). The Cainozoic strata in several regions yield lignite or brown coal, as in North Germany, Italy, and Washington, U.S.A. The mining engineer who may be on the outlook for coal will do his best, therefore, to discover fossils—the presence of which will determine the geological horizon of the strata. Should the fossils prove the strata to belong to an older period than the Carboniferous, workable coals are not likely to be met with. Hopes, however, may be encouraged should the rocks prove to be of Carboniferous or later age. In such a case the engineer would endeavour to ascertain the general character of the strata. Should thick marine limestones be present in the series, and the accompanying shales and sandstones yield only brachiopods, cephalopods, and other types of marine life, and should few or no traces of land-plants occur, then there would be little probability of discovering workable coal-seams. Should the strata, on the other hand, consist of rapidly alternating beds of sandstone and black or dark coloured shale with occasional seams of clay, and layers of clay-ironstone—such a succession might be considered hopeful. The appearance here and there of thin limestones of marine origin would not necessarily be an adverse sign, for coals and limestones are well known to occur, now and again, in one and the same group of strata. But should the constantly recurring beds of shale contain plant-remains, often very well preserved, while the sandstones showed streaks and thin lenticular layers of coaly matter, and the clays were charged with rootlets, our hopes of encountering coal would be greatly increased. It must be remembered, however, that the occurrence of black shales is not of itself a sure indication of the presence of coal in any series of strata. In almost all geological systems, particularly in some of the older Palæozoic formations, black shales may occur without the accompaniment of even the most exiguous seam of coal. Let us suppose, however, that our engineer has encountered a succession of strata closely resembling those which in other parts of the world have yielded coal-seams. He naturally examines carefully every rock-section in the hope of discovering outcrops of the fossil fuel. This hope, however, might not be realised, for, owing to weathering, sections are often rendered more or less obscure, and outcrops of readily yielding beds are frequently concealed under sheets of débris. Search in the alluvial deposits of the valleys, however, might be rewarded by the discovery of fragments of coal, and the source of these would be tracked up-stream in the usual way (see p. 289). Were the region not thickly covered with superficial accumulations, outcrops of coal might be expected to betray their presence by the blackened soils and subsoils resting upon them.

Having satisfied himself as to the presence of coal, the engineer would proceed to open up any outcrop, so as to ascertain the thickness and quality of the seam, and the nature of the "roof" and "floor." Should the coal be too thin or too poor in quality to pay the cost of working, we should not necessarily give up all hope. The engineer would probably suggest that before abandoning the search the ground should be proved by putting down one or more bore-holes. Before any such attempt is made, however, the geological structure of the area ought to be worked out, the character of the strata most carefully noted, and some reasonably clear notion formed as to the conditions under which the strata have been accumulated. It may be that the coals are persistent at definite horizons throughout the whole area, or, on the other hand, they may be merely lenticular seams of no great extent, and occurring at irregular intervals. In the former case, it is obvious that a valuable coal-field would be waiting development, while in the latter case the chances of striking a workable seam might be too uncertain to attract the attention of capitalists.

Careful investigation of the exposed sections should enable the observer to decide the question. If he be a geologist he will know that coal has been formed in two ways: sometimes it represents swampy accumulations—the accumulated growth of plants *in situ*—at other times it would appear to consist of drifted vegetable débris. In either case the fossil fuel has resulted from the chemical alteration of vegetable matter while excluded from the action of the atmosphere. Coals vary much in character—even individual seams vary considerably, being more or less bituminous as the case may be. These differences are doubtless largely due to the nature of the original vegetable débris. Certain parts of the plants of Carboniferous times, for example, were more resinous than others, and when such enter largely into the formation of a seam we have usually a highly bituminous coal. The cones and spikes of the vascular cryptogams and the gymnosperms shed abundance of resinous spores and pollen, while some of the old coal-trees seem to have secreted resin—the cortical substance of certain types being traversed by tubes and canals which are believed to have been connected with this function. Leaves, woody matter, and bark constitute the major portion of most mineralised coal.

The two views at present maintained as to the mode of formation of coal-seams may be very shortly described.

(a) *Growth in Situ.*—This is thought to be the probable origin of coal-seams that retain a tolerably uniform thickness over extensive areas, and which rest on clay or shale containing abundant rootlets. Seams of this kind are supposed to have been formed much in the same way as mangrove- and cypress-swamps. The vegetation may have been developed partly on the low flat shores of estuaries and bays, and partly in the salt water itself, for marine shells now and again are found closely associated with such coal-seams. Many successive beds of coal may occur in a very thick consecutive series of sandstones, shales, clays, etc.—all these beds having been laid down in relatively shallow water. Such a succession would indicate accumulation during a prolonged period of subsidence—interrupted, perhaps, by longer or shorter pauses. Each coal with its underclay would in this view represent such a pause in the movement of subsidence.

(b) *Drifted Vegetable Débris.* — Some coals cannot possibly have resulted from the growth of plants *in situ.* This is proved by the constant dovetailing and interosculation of such seams with shale and sandstone, and by the very irregular thickness of the coals themselves. Well-preserved ferns, leaves, branches, etc., may abound in the beds immediately underlying, and particularly in those overlying such coals. Now and again stems of trees in approximately upright positions occur in the associated sandstones. Their appearance is suggestive of flotage —for a long bare stem, crowned atop with an abundance of leafy branches, and weighted below with its thick but-end and roots, would tend to sink in a more or less upright position, swaying over, perhaps, in the direction followed by the transporting current.

The occurrence of numerous partings of shale in certain coal-seams, and the fact that such partings thicken-out in many cases so as eventually to separate one coal-seam into two or more seams, divided the one from the other by many feet or yards of sedimentary strata—are hardly consistent with the theory of growth *in situ*. Nor does this theory account satisfactorily for the well-known fact that individual coal-seams often consist of different kinds of coal, occurring one above the other in irregular lenticular layers, or in more or less persistent seams. For example, many common coals contain interlaminations of cannel coal, which may be an inch or two in thickness, while some layers of certain common coals are more bituminous than others. Further, it may be noted that fish-teeth, and shells of what were either fresh-water or brackish-water molluscs, now and again occur in coals or in the shales immediately associated with them ; even marine shells, as we have seen, occasionally appear in connection with coals. In the Scottish coal-fields, indeed, thin coals not infrequently are underlaid or overlaid directly with calcareous shales and thin limestones, throughout which marine organic remains abound. These phenomena are very hard to explain in any other way than by supposing that such coals were accumulated in water —that, in short, they are sedimentary formations. It has been objected that the comparative purity of coal—the relative absence of sand and mud—is against the supposition that coal could have been accumulated by drift. It is obvious, however, that vegetable matter carried down by streams and rivers into lakes and estuaries does not necessarily become impregnated or mixed up with ordinary sediment. When a river enters an estuary, its sediments become sifted out—the finer ingredients being spread over the widest area. Should the river carry rafts and sheets of vegetable débris, these may well be transported far beyond the reach of ordinary sediment. Becoming waterlogged, this vegetable débris would eventually sink, and might therefore come to rest in regions rarely or never reached by ordinary sedimentary matter. It is quite conceivable, therefore, that over the floors of estuaries and broad bays, at some distance from the land, vast accumulations of vegetable detritus might take place. The interosculation of such sheets of vegetable matter with sand and clay is just what one would expect to occur, while the occasional appearance of fresh water, estuarine, or marine organisms need not surprise us, for the accumulation of vegetable débris might take place either in large rivers, in lakes, in estuaries, or in more open bays of the sea. It is obvious, moreover, that the drift hypothesis offers a feasible explanation of the variable character of many coals, and accounts well enough for the frequent intercalation in the sandstones of thin lenticular layers and beds of coal and coaly matter.

Although the observer may have assured himself that only thin coals crop out at the surface, he need not, on that account, conclude that further research is useless. It is quite possible that the seams seen in actual section may thicken-out as they are followed downwards. But if the strata are undulating and the same beds come again and again to the surface—each recurring coal-seam continuing thin and unimportant—he will have good reason to infer that the series is not worth further investigation. Should the rocks, however, be partially concealed by overlaps or unconformities or by faulting, or otherwise not be accessible, owing, perhaps, to thick coverings of surface accumulations or to the paucity of sections, the observer would not be wise to abandon his search. The occurrence of thin seams of coal, or even the mere presence of numerous plant-remains such as are commonly associated with coal-bearing strata, taken in connection with the obviously shallow-water origin of the strata and the absence of any evidence of deep-sea or purely marine conditions, would be sufficient to justify trial-boring. The frequent occurrence of rootlet-beds, with or without overlying coal-seams, would suggest the probability that the unexplored parts of the series might contain more or less persistent beds of coal. The absence of rootlet-beds, however, would not be quite so favourable a sign. It would lead to the inference that any workable coal-seams that might occur would be apt to be somewhat inconstant—lenticular sheets, thickening and thinning irregularly. But, inasmuch as seams of this character not infrequently attain a very considerable thickness and extend over wide areas, it would obviously be important to ascertain the direction in which thickening was likely to take place, and thereafter to test the ground by borings.

The Search for Ore-Formations.—Bedded ores occur under the same conditions as any other sedimentary rock, and are therefore to be sought for and traced by the ordinary methods employed in field geology. The same to a large extent is true of lodes and irregular ore-formations of all kinds, but the search for these is not, as a rule, so easy. Perhaps most discoveries of such ore-deposits have been the result of accident. A large number, however, must be credited to those sanguine and often admirable observers, known as "prospectors," the most successful of whom have, wittingly or unwittingly, usually followed geological methods of research. Having become familiar with the ore-formations of some particular region, and learned to recognise the manifold appearances presented by them at the surface, such as the coloration of soils and subsoils, the character of the gossans, etc., a prospector could hardly fail of success so long as his researches were confined within the same geological area. Should the same observer, however, essay to prospect in a totally different region, he might often be nonplussed. In point of fact, many mining men have wasted time and substance in exploring wide tracts of country which a knowledge of geology might have led them to avoid, as probably barren ground; while, on the other hand, such knowledge might have directed their attention to areas in which prospecting was likely to lead to successful results.

Lodes and irregular ore-formations may occur in almost any kind of rock, and are not restricted to a particular geological horizon, for they are met with in Palæozoic, Mesozoic, and Cainozoic rocks alike. But although this is true, yet by far the larger number of such formations are associated with the older geological systems. It is exceptional to meet with valuable lodes, etc., in Cainozoic and even in Mesozoic rocks, except in the vicinity of eruptive masses. Most lodes, etc., are of more or less deep-seated origin, and are thus least likely to be met with traversing rocks of relatively late geological age. They are, therefore, to be sought for in the more ancient rocks, because these have experienced vast denudation, their present surface in many cases being several thousand feet or yards below that which existed at the time the lodes were being filled. It must not be supposed, however, that every region of highly denuded ancient rocks is likely to contain valuable ore-formations. We know, in fact, that such is not the case; but certainly it is to such regions that the prospector ought to turn his attention. The more highly folded, fractured, and dislocated the rocks are, the better from his point of view, while the presence of batholiths, sills, and dykes of eruptive rock would be rather a hopeful sign, as will be gathered from what has been set forth in Chapters XVI. and XVII. as to the mode of occurrence and origin of ore-formations.

Let us suppose, therefore, that an explorer has entered a sorely denuded hilly or mountainous region of ancient rocks—the general character and geological structure of which seem favourable. It is obvious that he must be guided in his investigations by the principles already illustrated in connection with geological map-making. He must be on the outlook for every indication that may lead him to the hidden treasure. Any marked change in the form of the ground will be noted—such as a prominent narrow ridge running in a linear direction—or a like well-marked hollow. The former may mark the outcrop of a lode of harder consistency than the rocks it traverses, while the latter may indicate the back of a vein filled with less resistant mineral matter. Even when the outcrop of a lode produces no marked surface feature, it will yet, in many cases, betray its presence by more or less pronounced coloration of the soil. This is due, of course, to the decomposition of the minerals occurring in the vein. Very frequently the overlying soil will be stained red or yellow, owing to the presence of iron-oxides, which are of common occurrence in most gossans. Other minerals, if sufficiently abundant, will indicate their presence by various tints or hues. Green colours, for example, are yielded by ores of copper, nickel, or chromium; commingled blue, green, and red stainings are yielded by copper ores; lead-ore is often indicated by yellow and green stainings; manganese-ores are black, while auriferous quartz is often rusty and cellular from the removal of pyrites. Again, a lode may be indicated by springs coming to the surface along a definite line, for lodes often act as subterranean dams ponding back the water that descends towards them along the various division-planes of rocks, and forcing it to the surface. Such springs not infrequently contain much mineral matter in solution, and may give rise to superficial accumulations of tufa, limonite, etc. Should the water contain deleterious ingredients (derived, for example, from the decomposition of iron pyrite), it will naturally produce a more or less striking effect upon the vegetation. A pyritous lode is, in this way, sometimes indicated by the poverty-stricken character of the vegetation in its immediate neighbourhood, which may be in strong contrast with that covering the country-rock.

Fragments of veinstone and ore occurring in a water-course will naturally be suggestive, and should the fine gravel and sand of the stream contain grains and particles of gold or other valuable mineral, the prospector—always a sanguine man—will feel confident of success. Stopping ever and anon, as he proceeds up-stream, to examine the contents of the alluvial deposits, he may at last reach a point above which no fragments or particles of metal or ore can be found. Searching the adjacent valley slopes, the observer discovers perhaps scattered fragments of veinstone and possibly ore. But whether these do or do not occur, the prospector would certainly be justified in digging pits or trenches down to the solid rock, in hopes of striking the ore-formation itself. While the search for such formations is, for obvious reasons, most promising in valleys, yet the land-surface separating one valley from another—more especially if it be a hilly region—must not be neglected. For, owing to long-continued weathering, such surfaces are often sprinkled in places with angular fragments, or partly mantled by sheets of rock-rubbish. Should lodes traverse such a tract, they are almost sure to be betrayed, even in the absence of conspicuous outcrops, by the presence of loose fragments, or *shode-stones*, as they are termed by Cornish miners. By the careful tracking of these stones their source may be located. It need hardly be added that the prospector who has a good working knowledge of ores, and is quick to understand leading geological structures, is more likely to succeed than the geologist who, however expert he may be in unravelling and interpreting rock-structure, is yet unfamiliar with the various "indications" that reveal so much to a keen-eyed mining man. The latter, however, whose experience may have been gained in some limited region, is often at a disadvantage when he begins prospecting in a new country. Not infrequently he is possessed with the belief that the mining region in which he was brought up must be the type of all others. If the only valuable lodes of that region have a north and south direction, he expects that the same is likely to hold good elsewhere—no matter what the geological structure of the ground may be. He often makes similiar assumptions as to the gossans. The auriferous reefs of the country he has left may crop out as ridges of ferruginous cellular quartz, and when similar gossans are encountered in a totally different area, he is apt to jump to the conclusion that these also must be gold-bearing, although not a trace of gold may occur either in the gossans or the veins they cover. Experience has shown, therefore, that it is never safe to infer that the appearances presented by the shode-stones and gossans of one region must necessarily be characteristic of mineral regions elsewhere. They may or may not be, but only by careful examination of the gossans and the unaltered veins below can doubt be set aside.

Although lodes and irregular ore-formations occur more commonly in association with the older geological systems, yet under certain conditions Mesozoic and even Cainozoic rocks have become charged with valuable ores. The most important ore-bodies of this late age are met with in the vicinity of massive igneous rocks (andesites and rhyolites) in volcanic regions which have experienced much erosion. The ores in question frequently appear as contact-formations, and the prospector, therefore, should do his utmost to trace the line of junction between such an intrusive mass and the rocks it traverses. Should the effects of solfataric action be manifest, this will be so far a favourable sign, since it is just under these conditions that fissures and faults have in many cases been filled with ores and other minerals, and the adjacent "country-rock" has been impregnated. Now and again, however, the observer finds that denudation has not yet laid bare the intrusive masses from which heated solutions have been derived—they still lie more or less deeply buried underneath the strata which have been affected by them. Their presence is suggested, in the first place, by the changes which these rocks have undergone. The latter are often much disturbed, shattered and brecciated, and frequently highly silicified—shales being converted into hard, siliceous porcellanite, and limestones into quartzose marbles, while felspathic rocks are usually kaolinised. Moreover, dykes of quartz-porphyry, etc., are often more or less plentifully present. Native gold and various ores of silver, antimony, mercury, arsenic, etc., frequently impregnate and are disseminated through the silicified rocks under such conditions. The great volcanic tracts bordering the Pacific in North and South America, and the corresponding volcanic regions of Japan and other islands on the opposite side of that ocean, are in places notable for their ore-formations, many of which are of late Mesozoic and Cainozoic age. There can be little doubt, however, that the mineral wealth of those lands is as yet very imperfectly known, and that many rich mining-fields still remain to be discovered by properly qualified prospectors.

Geological Structure and Engineering Operations: Excavations.—In the construction of roads, railways, and canals, the nature of the rocks to be excavated must be ascertained before any estimate can be formed of the probable cost of an undertaking. Where the rocks themselves are not exposed to view, the engineer usually digs pits or puts down shallow bore-holes, and bases his estimate on the information thus obtained. The evidence is often quite sufficient for his purpose; at other times, however, it is inadequate, and may even be misleading. In the case of deep excavations and in the driving of tunnels, for example, something more than a mere knowledge of the rock immediately underlying the subsoil is required. Before undertakings of that kind are entered upon, the engineer ought to make a thorough examination of the geological structure, for the nature and character of the rocks at the surface may afford no indication of the nature of the rocks and rock-structures to be encountered at a short distance below.

In all such engineering operations it is most important to ascertain (*a*) the lithological character of the rocks to be penetrated, and (*b*) the mode of their arrangement or, in short, the geological structure. It is obvious that the actual cost of excavating will depend, in the first place, on the relative hardness of the rocks, and the ease with which they can be extracted, which will often be determined by the nature of the jointing. The engineer has further to consider whether the rocks, when cut through, are likely to be self-supporting, and of sufficient durability to withstand the action of the weather. Here the question of geological structure comes in, for it is obvious that a rock exposed in vertical section may be sufficiently durable if it be horizontally bedded, but quite untrustworthy if it be inclined in the wrong direction. The behaviour of the rocks with regard to the circulation of underground water has also to be taken into account. A highly permeable rock exposed in section may weep so copiously through pores or joints, that it is readily broken up when exposed to the atmosphere.

As it is hardly possible for the engineer to consider the lithological character of rocks apart from their geological structure, we may briefly indicate how strata may be expected to behave in cuttings according as they occupy horizontal or inclined positions.

When homogeneous firm rocks which show very few joints are horizontally disposed, they may usually be relied upon to be self-sustaining, and to stand with approximately vertical faces in any open cutting. Such rocks are permeable only to a limited extent, and throw out little or no water. Hence, even when they occur as a series of thick beds separated by intervening layers of impermeable shales or clay, springs are of infrequent occurrence. Where the rocks to be cut through consist, on the other hand, of a series of highly porous and jointed beds with intervening impermeable shales, etc., springs and seepage may be expected. Even should water not filter through into the cutting, it is obvious that beds of such varying character are sure to weather unequally—the softer rocks will crumble away, and constant undermining of the overlying beds must take place. Under such conditions, it becomes necessary to bench back the cutting, or to slope it until the angle of repose is reached. But where much water is discharged, the engineer may be compelled to mask the cutting with impervious masonry, apertures being left in the wall here and there to allow the water to escape.

When strata are excavated in the direction of their dip, they can usually be treated as if they were horizontally bedded. The point of most importance is the nature of the rocks themselves. If the beds are firm and relatively impermeable, they may be expected to stand with vertical or nearly vertical faces. The chief dangers to be guarded against are the escape of water and the action of frost.

Cuttings made in the direction of the strike usually require different treatment. On one side of such an excavation the beds dip away from the line of cutting, and therefore occupy a strong position. Even should they consist of a series of alternating porous and impermeable rocks, they will often stand with a vertical face. The reason is obvious, for any water the porous beds may contain will tend to escape downwards along the planes of bedding—it is drained away from the cutting. On the opposite side of the excavation, the strata dip into the cutting and therefore occupy an unstable position. The tendency is for the truncated beds to slide downward; and should they consist of alternating pervious and impervious beds, springs will come out, undermining will take place, and piecemeal or wholesale collapse must result. Rocks occupying such a position must be built up, care being taken to allow passage for the percolating water.

Excavations in massive igneous rocks will often stand with vertical or approximately vertical faces. The character of the jointing, however, has to be carefully considered, and the possible action of springs, in undermining and dislodging masses, and the general effect of frost, must not be overlooked. Schistose rocks, in like manner, are often firm and stable when opened up, more especially if the excavation runs in the same direction as the dip of the foliation. But when the cutting traverses such rocks along the strike, they are apt to behave much in the same way as sedimentary strata—on one side of the excavation they may be expected to stand well; on the opposite side slips and falls are likely to take place. Their stability, moreover, is often affected by the very irregular jointing, and by the variable character of the rocks themselves; so that while some schists readily allow the passage of water, others are more or less impermeable. The stability of this class of rocks further depends, to some extent, upon the nature of the foliation. Evenly foliated rocks, which simulate ordinary sedimentary strata, may be expected to behave much in the same way as the latter. When schists are much crumpled and contorted, however, the individual folia are more securely locked together, and slipping is much less likely to take place, so that such rocks may often be treated as if they were highly jointed igneous masses. Slates, it need hardly be said, more closely resemble steeply bedded sedimentary rocks, such as greywackés and shales, the stability of the faces of a cutting depending upon the direction of the planes of cleavage. Should the latter be traversed at right angles, the rock on both sides of the cutting will stand with vertical faces. When an excavation, however, is carried in the same direction as the strike of the cleavage, the rock will necessarily be more stable on one side than the other. In a word, the superinduced cleavage-structure plays the part of lamination and bedding in the case of sedimentary strata.

It is not necessary to add more than a word as to excavations in incoherent and non-consolidated rocks. Rocks of this kind will not stand with a vertical face, except in rainless or all but rainless regions. Under ordinary conditions, therefore, the engineer, in excavating soft, incoherent masses or beds, has to consider the slopes he must give to the sides of the cutting, for the angle of repose varies directly as the nature of the materials. Even in such cases it will usually be found that geological structure has its influence. Should the incoherent beds have a dip and be traversed at right angles to their inclination, they will almost invariably stand better on one side of a cutting than the other. Any water that may permeate the beds will tend to come out rather on the "weak" than on the "strong" side; slipping will be apt to take place from time to time on the former, but not so readily on the latter.

Tunnels.—If it be unwise on the part of an engineer to undertake important excavations or open cuttings without having previously examined the geological structure of the ground to be traversed, he would be deserving of censure if, before driving an important tunnel, he did not first endeavour to ascertain every fact connected with the rocks and their arrangement. In the case of horizontally bedded strata, not much difficulty would arise; the tunnel would be driven practically along the planes of bedding, and the character of the rock at the two ends of the proposed tunnel could be readily ascertained, and thus a reliable estimate of the cost of the work could be formed. But if the strata were not horizontal, then even the most careful examination of the rocks at either end of the proposed tunnel might deceive the engineer who had neglected to ascertain the geological structure. The annexed diagram (Fig. 125) represents the geological structure of a hill which it is proposed to tunnel along the line *a b.* It is obvious that shallow pits and borings put down over the surface can give no indication of the nature of the rocks which the tunnel is likely to pierce. An engineer, finding that the rock over the top of the hill and at the two extremities of the proposed tunnel, were all of a reliable kind, might probably conclude that the whole hill was composed of like materials. If the rock happened to be of a self-supporting nature—one that required little or no expensive building—he would frame his estimates of cost accordingly. A knowledge of the actual structure, however, would have shown him that the self-supporting stratum could continue but a short distance on the level of the proposed tunnel, and would then be succeeded by friable shales requiring support all the way to near the middle of the hill, where highly porous and water-logged sandstones might be expected to add still further to the difficulties and cost of the undertaking. The history of engineering operations in this and other countries is full of warnings as to the danger of driving tunnels without having first determined the geological structure of the ground. Not infrequently, this requisite knowledge might have enabled the engineer to avoid difficulties and greatly increased cost by some slight deviation of the line of his tunnel or by modifying the gradients. Even in cases where such deviations and modifications may be impossible, a knowledge of the difficulties lying before him would yet greatly aid the engineer in making his estimates.

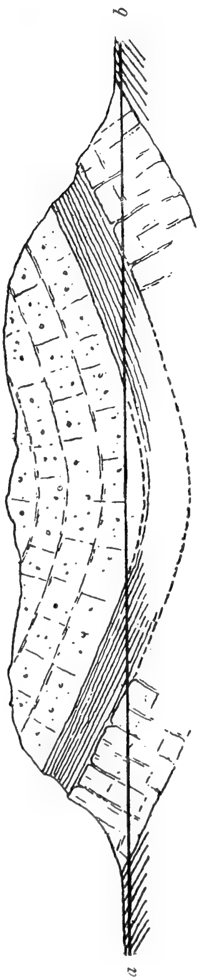


FIG. 125.—TUNNEL THROUGH SYNCLINAL STRATA.

Foundations.—Engineers and architects are necessarily called upon to consider the nature of the foundations on which it is proposed to build heavy structures. Trial holes will show the nature of the materials, but they do not always disclose the geological structure, and in the case of very heavy buildings it is absolutely essential that the latter should be carefully ascertained. For, however solid and unyielding the substratum may seem to be, calculations as to its stability are liable to error if its relations to the immediately subjacent rocks be not taken into account. For example, a firm massive sandstone may be underlaid by some impervious slippery clay, which, should the strata have a decided dip, may yield to the great pressure of a heavy superstructure, and cause the rock-foundation to slide forward along the plane of bedding. Unconsolidated materials often make bad foundations, but tough, homogeneous clay, if of sufficient thickness, is usually reliable. Alluvial or superficial deposits of every kind, however, are as a rule unsatisfactory, and, in the case of important structures, usually require special treatment, involving often costly excavation, the driving of strong and closely set piles, and the formation of an artificial foundation of concrete. Although tough clays, such as the boulder-clay of the Scottish lowlands, usually form reliable foundations, they nevertheless are sometimes untrustworthy. Not infrequently they contain layers and beds of gravel and sand that carry water, which, when it escapes at the surface, tends to undermine the overlying mass, and thus in time causes the ground to subside. Before any heavy building is raised upon till, therefore, it is necessary to ascertain by means of boring whether any water-bearing beds be present. The river-valleys of Central Scotland afford many examples of the relative instability of boulder-clay, when that deposit rests upon an inclined surface of rock. In the valley of the Esk, for example, almost every house and wall built upon the slopes overlooking the valley-bottom afford evidence in their cracked masonry of a slow and interrupted but nevertheless continuous slipping of the foundations. The cause is obvious: the boulder-clay, which has a coarse, rubbly bottom, rests upon an inclined surface of sandstones, shales, etc., from which water escapes and percolates through the stony and rubbly base of the clay. The latter thus becomes softened and slippery, and from time to time yields, and the mass creeps downwards. The boulder-clay, under such conditions, is in a state of unstable equilibrium, the risk of slipping increasing with the slope of the surface on which the clay reclines.

CHAPTER XXIII

ECONOMIC ASPECTS OF GEOLOGICAL STRUCTURE—*continued*

Water-supply. Lakes and Impounded Streams. Reservoirs. Supply from Rivers. Underground Water — the Water-level; Natural Springs as illustrating the course followed by Subterranean Water; Surface and Deep-seated Springs. Common Wells and Driven Wells. Artesian Wells. Considerations to be kept in view in the search for an Artesian Water-supply. Drainage. Distribution of Disease in relation to Geological Conditions.

Water-supply.—Superficial and underground sources of supply alike depend upon the amount of precipitation and the physical aspect and geological conditions of a country. But the relative amount of water circulating above and below ground respectively is determined mainly by the character of the rocks and the mode of their arrangement. Two regions, for example, may have the same amount of rainfall, and, nevertheless, the one may be little better than a dry desert, while the other may rejoice in numerous streams and rivers, and be conspicuous for its fertility. There are many lands that consist of rocks so highly pervious that rain and melting snow at once descend below the surface, and streams and rivers are impossible—all the drainage being conducted underground. On the other hand, we may encounter elsewhere the opposite extreme—namely, a country built up of impermeable rocks which absorb so little water that practically the entire rainfall flows in superficial courses to the sea. Between these two extremes there are many gradations—most lands being composed partly of porous and partly of impermeable rock-formations.

It will be convenient to treat of the water-supply derived from superficial sources apart from that obtained from underground stores, although it is obvious that much of the water that circulates in our streams and rivers has come from springs.

Lakes and Impounded Streams.—The character of the water of a lake naturally depends upon that of the catchment area, for it is needless to say that the level of the lake is maintained by the rainfall—in other words, by the springs and streams that feed it. Should the rocks within the drainage area be largely calcareous the water will be *hard;* should igneous and schistose rocks predominate, the water will be moderately *soft.* Other things being equal, the deeper and larger a lake is, the purer and colder must the water be. Large and deep lakes occupying mountain valleys, like those of our own islands, where there is little or no cultivation and not much chance, therefore, of contamination, are always desirable sources of water-supply. But every country is not so fortunate in the possession of large natural reservoirs, and even when these exist they are often so far removed from centres of population as to be practically beyond reach. Under such circumstances, engineers are required to form artificial lakes by impounding streams.

Reservoirs.—The formation of reservoirs is purely an engineering operation, but, like many other undertakings of the kind, it ought to be conducted with a full knowledge of the geological conditions. If we have the choice of several streams, it is obvious we should select the purest. Those which are most likely to yield a desirable water-supply will usually occur in sparsely cultivated districts which are not likely in the future to attract much population, such as the high-lying pastoral regions of our own country. Before selecting a stream, however, the character of the rocks within the drainage-area should be carefully inspected, for the purpose of ascertaining whether these contain deleterious ingredients which might unduly affect the character of the water-supply. Usually, however, careful chemical analyses of the water flowing in the main stream at all seasons of the year will determine the suitability or otherwise of the supply. A desirable stream having been obtained, the engineer's next care is to select a site or sites for his storage reservoirs. It is at this stage of his work that he will find a knowledge of structural geology most helpful. He should carefully investigate the rocks occupying the proposed site, in order to satisfy himself as to their soundness. Should they be very porous and much shattered and jointed, the conditions will be unfavourable, and a better site, if possible, should be sought for. This will be all the more advisable should the strata in question be inclined in the same direction as the valley, for under such conditions leakage is almost certain to take place —much water escaping along the bedding-planes, not to reappear at the surface, perhaps, till after an underground course of many miles. Should the inclination of the strata, however, be in the opposite direction, there is not the same danger of considerable loss, since any water that finds its way below the surface may possibly be discharged again further up the valley. It is needless to say, however, that no engineer would think of forming a reservoir over an area of highly jointed and pervious rocks, if he could avoid doing so. Unfortunately, the bottom of a valley is frequently covered with thick alluvial deposits, and the engineer, unless he knows something of geological structure, may not be aware of the nature and arrangement of the underlying rocks—even after he has tested the ground by means of boreholes.

The selection of a site for his *embankment* demands the greatest care. Sometimes there is no difficulty—the bed of the valley may be deeply filled with tough, homogeneous clay, than which no better foundation could be obtained. It is always well, however, to make sure by a series of borings that no water-bearing beds are present in or underneath the clay, for in either case these would be sources of danger—allowing of leakage, and thus threatening the stability of the embankment. As foundations for an embankment, highly jointed rocks of any kind—certain igneous rocks, limestones, and loose shattery shales especially—are to be avoided. When the engineer has no choice of sites, but must, if at all possible, build his embankment upon rocks, the character and structure of which are quite unfavourable, the difficulties he must encounter will add greatly to the cost of the undertaking.

Rivers.—Some towns and cities draw their water-supplies from the rivers on which they are situated. In certain cases the water is pumped from some point above a town, while in other cases it is drawn from the higher reaches of the river and brought in open courses or in pipes. This source of supply is seldom desirable, but not infrequently no other source is available, in which case the only thing to be done is to look well after the filtering, which doubtless minimises the danger of pollution, but cannot always be implicitly relied upon to protect the population. It is remarkable, however, how rapidly rivers seem to purify themselves from the pollutions poured into them by the villages and towns upon their banks. Soon the water begins to clear—a foul-smelling mud settling upon the stones and gravel of their beds, and gathering here and there in extra quantities along their margins. Exposed to sunlight and the action of the atmosphere, the various organic impurities become broken up—a process in which numerous minute forms of life play a not unimportant part—until eventually the river may become bright and sparkling as at first. All such waters, however, are properly held suspect, and ought never to be used for domestic purposes before they have been carefully examined and declared safe.

Underground Water.—The proportion of the rainfall that sinks into the ground naturally varies according to the character of the underlying rocks. But, whatsoever the nature of the rocks may be, they are commonly charged with water up to a certain limit known as the **water-level,** the depth of which from the surface is determined by the amount of rainfall, the configuration of the surface, and the geological conditions. In some districts, the level in question may be reached at only a few yards down; in other places it may sink to great depths, and it usually fluctuates with the rainfall. Owing to these several conditions, a constant underground circulation is kept up—gravitation and hydrostatic pressure forcing the water through the pores and fissures of the rocks until it can escape at the surface in the form of springs. In regions composed chiefly of highly pervious rocks of great thickness, springs are of infrequent occurrence, and are apt to appear only in the deeper depressions of the land. But in countries where the rocks are of variable character and structure, underground water may be discharged at many different levels, in mountain regions and low grounds alike; not infrequently, indeed, copious springs of fresh water coming from such regions issue on the floor of the sea. The various divisional planes of rocks—joints, bedding-planes, faults, etc., naturally constitute the chief underground water-ways. In the case of soluble rocks these water-ways become widened by the chemical and mechanical action of the running water, until very considerable tunnels may be worked out—giving passage to torrents, streams, and rivers. Relatively insoluble rocks are not, of course, traversed by subterranean channels of this kind, but, if sufficiently porous, they frequently contain enormous stores of water. When such beds are inclined and underlaid by impermeable strata, the water they contain naturally makes its way downward in the direction of dip. Should the strata be horizontal, underground flowage nevertheless does not cease—the water under hydrostatic pressure being forced to percolate through the rocks. Such movements, indeed, necessarily take place even in amorphous rocks which are neither bedded nor jointed.

In the following case (Fig. 126) we have, say, an amorphous mass of sand and gravel (*a*) resting upon a horizontal surface of impervious clay (*b*). Rain falling on the surface of *a* is greedily absorbed, and gradually sinks until the bed becomes saturated up to a certain limit (*w*), when the frictional resistance to its passage outwards is overcome by the hydrostatic pressure. It is then forced to flow along the surface of the underlying clay, and escapes to the light of day at *s s* as a line of seepage marking the junction between the porous and impervious beds; but should there be irregularities in the surface of the clay, it may issue in the form of definite springs. Springs of this kind are of common occur-

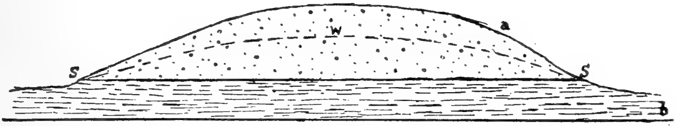


Fig. 126.—Heaping up of Water in Superficial Deposits.

rence in horizontally bedded rocks of varying character, some being pervious, others impervious, for every porous stratum is likely to contain a store of water which will ooze or flow out wherever the beds are truncated, as on hill-slopes and in valleys (Fig. 127).

Generally, however, strata are more frequently inclined than horizontal, and through these water flows under the combined influence of gravitation and hydrostatic pressure. When such strata are traversed by a valley running in the direction of strike, underground water tends to be discharged only on one side, namely, on that side from which the truncated beds dip into the valley. If the beds dip at a high angle, the springs will usually be insignificant, since with a high dip the outcrops will be narrow; with a low dip, on the other hand, the discharge will be proportionately greater, for the simple reason that the outcrops of the porous beds will spread over a wider area, and be thus capable of imbibing a larger proportion of the rainfall.

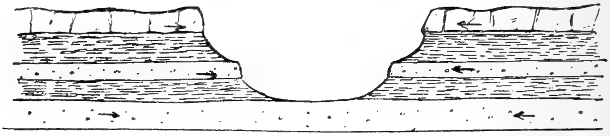


FIG. 127.—DRAINAGE IN HORIZONTAL STRATA.

Synclinal valleys are of rare occurrence, especially in regions which have experienced much denudation; but when they do occur amongst water-bearing and impervious strata, springs may abound on both sides of a valley (Fig. 128). When a valley coincides with an anticline, however, the

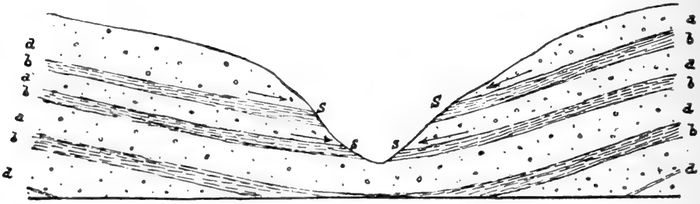


FIG. 128.—DRAINAGE IN SYNCLINAL STRATA.

geological structure is obviously quite unfavourable to the outflow of underground water, the water, as in the previous cases, making its way in the direction of dip (Fig. 129), and therefore away from the valley.

We have been considering the flow of water through porous rocks as being conducted along the planes of bedding, but we must not forget that sedimentary strata are traversed by joint-planes, and that the presence of these naturally influences the circulation. When all the porous beds in a series of strata are fully saturated, the water will follow the normal direction. But when continued dry conditions have cut off the supply from above, and the discharge by springs begins to diminish, water seeks its way down through joints and fissures from one porous bed to another. Hence the springs issuing from the deepest beds will continue to yield their usual supply long after the highest lying springs have failed. The exhaustion of the springs may be still further delayed by the exuding of water from the less porous beds—all of which, although spoken of as impermeable, are yet capable of absorbing and giving out water in less or greater degree.

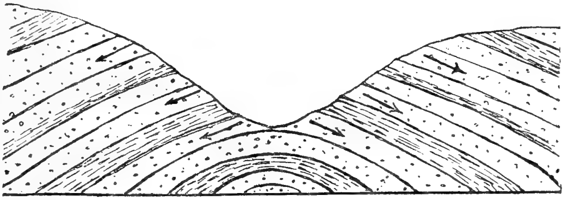


FIG. 129.—DRAINAGE IN ANTICLINAL STRATA.

Springs are not less characteristic of massive eruptive rocks than of sedimentary beds, but while the underground drainage of the latter is conducted principally through porous strata, and therefore follows a determinate direction, that of the former keeps to the clefts and fissures, and as these vary in width and trend, and may be numerous in some places and far apart elsewhere, one never can tell where springs are likely to appear at the surface. Rain falling upon a granite mass finds its way down through innumerable fissures, and after a relatively short downward course may, under the influence of gravity alone, escape to the surface. Or after penetrating to a great depth—far below the level, perhaps, of any valley in the neighbourhood—it may have its passage impeded or barred by the closeness of the joints. Subject to great hydrostatic pressure, it will now be forced to ascend to the surface along the same kinds of fissures by which it travelled downwards, and will issue as a deep-seated spring, which may or may not have a temperature exceeding that of the region where it appears. It is not improbable, indeed, that meteoric water may sometimes descend by fissures to such depths that its further progress downward is arrested by the internal heat of the earth. The enormous pressure at a depth of several thousand feet will prevent ebullition, but expansion must result, and this, added to the hydrostatic pressure of the descending currents, will force the water through other fissures to the surface. Deep-seated springs of such a nature might either be cold or thermal (Fig. 130).

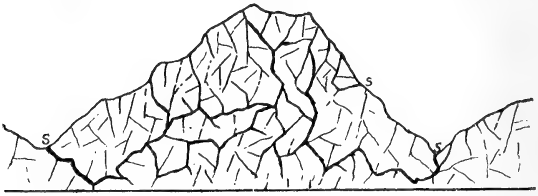


FIG. 130.—DRAINAGE IN MASSIVE IGNEOUS ROCK.

The underground drainage of schistose rocks is usually just as hard to determine as that of massive eruptives. Exceptionally, where schists are relatively well bedded and consist of a series of rocks, some of which are better water-bearers than others, springs will tend to appear at the outcrops of the latter. As a rule, however, owing to the abundant folding and the irregular jointing, the direction of the underground drainage among schistose rocks is quite indeterminate.

A large number of strong springs often appear along the line of junction between an intrusive mass and the rocks it traverses. The water may be derived either from the one or the other, or from both. In Fig. 131, for example, a great mass of granitoid rock is represented cutting across a series of relatively impervious strata. The rain passes downwards through the much-jointed eruptive mass, where it accumulates. The water cannot escape laterally, because it is dammed back by the impervious beds (*b*); it therefore continues to accumulate until it reaches the point where the line of junction comes to the surface. Here, under hydrostatic pressure, it flows out as a more or less copious spring (*s*) or line of springs. In many cases, however, the water is derived from the stratified rocks rather than the intrusive mass by which they are intersected. In Fig. 132, the strata, consisting of pervious and impervious rocks, dip towards the igneous mass. Water soaking through the porous beds (*p*) is dammed back by the basalt (*b*) and forced to the surface (*s*) along the junction-line. Now and again, the water discharged under such conditions would seem to come from the rocks on both sides of the junction, especially when the igneous mass is of the nature of a batholith, and exposed at the surface over a considerable area.

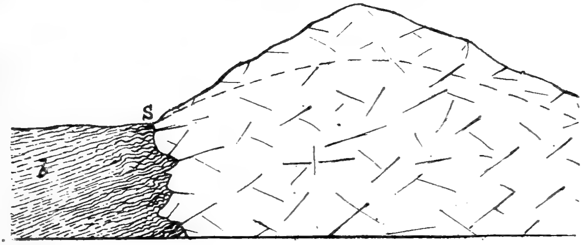


FIG. 131.—HEAPING-UP OF WATER IN IGNEOUS ROCK.

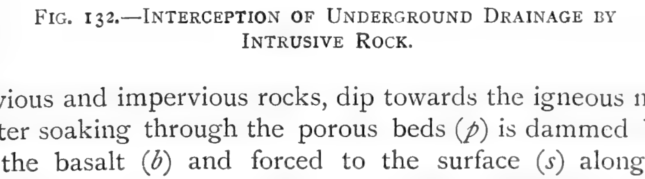


FIG. 132.—INTERCEPTION OF UNDERGROUND DRAINAGE BY INTRUSIVE ROCK.

Springs, as we have already seen, are often associated with those vertical wall-like intrusions, known as dykes (see p. 202). When dykes cut across inclined rocks in the general direction of the strike, they naturally act as subterranean dams, interrupting the underground water flowing towards them, and forcing it to rise to the surface (Fig. 133).

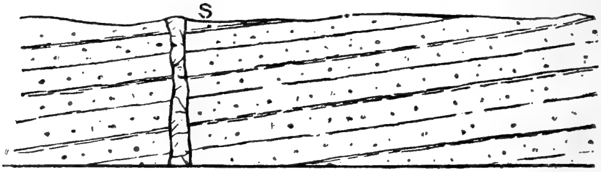


FIG. 133.—INTERCEPTION OF UNDERGROUND DRAINAGE BY DYKE.

Junction-springs of this kind are very common in Scotland. Probably the most important springs of all, however, are those that appear on lines of faulting or dislocation. These, as we have learned, frequently bring permeable against impermeable rocks, and many of the largest dislocations run in the direction of the strike of inclined strata. Hence, when a series of porous strata dip at a low angle for a long distance, towards one of these faults, on the other side of which the rocks are more or less impermeable, all the conditions favour the formation of strong springs (Fig. 134). Even when the strata on both sides of a fault are porous, springs will usually indicate its presence, for faults are often filled or lined with clay, etc., and thus form more or less impervious barriers, while the adjacent rocks, commonly much fissured and fractured, afford the underground water a ready passage to the surface. A fault traversing horizontal strata in such a way as to bring permeable and impermeable rocks into juxtaposition likewise causes springs to appear, whenever the

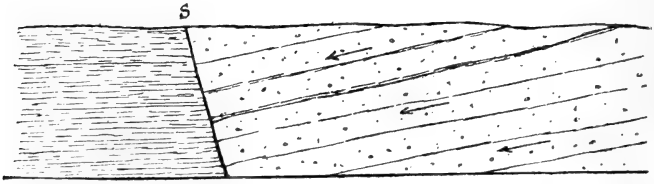


FIG. 134.—INTERCEPTION OF UNDERGROUND DRAINAGE BY FAULT.

water-level in the porous beds reaches the point where the fault touches the surface (Fig. 135)—the conditions being somewhat comparable to those represented in Fig. 131. Considerable dislocations, indeed, will usually carry water, even although the structure of the rocks they traverse may not seem very promising. For it will rarely happen that a normal fault, cutting across a great thickness of rock, will not, in some parts of its course, truncate water-bearing beds, the fluid contents of which are under sufficient hydrostatic pressure to rise to the surface. The faults themselves are often to some extent open fissures or filled with rock-rubbish which is easily penetrated; while the contiguous rocks on one or both sides are usually more or less fractured and jumbled: it is not surprising, therefore, that springs should occur along lines of dislocation, under the most diverse conditions. It will thus be seen that a knowledge of the faults of a district is highly desirable, if we would understand its subterranean hydrography.

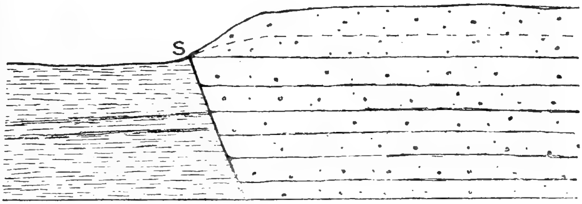


FIG. 135.—HEAPING-UP OF WATER IN HORIZONTAL STRATA.

Springs are usually classified as *shallow* or *surface* and *deep-seated*. A spring which fluctuates with the seasons—tepid in summer and cold in winter, and running full or drying up according as the rainfall is excessive or scanty—is obviously quite superficial, the water having come no great distance. Between temporary springs of this type and perennial springs whose volume remains practically constant, and whose temperature does not vary with the seasons, there are all gradations. Obviously, the most persistent springs derive their supplies from wide gathering grounds, those whose surface never rises nor falls probably coming from the greater depths.

Wells.—The foregoing rapid sketch of the conditions that determine the underground circulation of water and its discharge at the surface will suffice to indicate what course we should follow in searching for a subterranean water-supply. From the very earliest times, men have dug for water—a **common well** being simply a hole sunk below the water-level, into which percolation from the surrounding rocks takes place. In these advanced days, we now imitate Nature on a bolder scale, and by means of our boreholes produce more or less deep-seated perennial springs. Water is doubtless very generally distributed through the superficial parts of the earth's crust, but all rocks, as we have learned, are not equally absorbent, and the depth of the water-level from the surface is very variable. It is obvious, therefore, that before proceeding to sink a common well, we should first ascertain whether the geological conditions are favourable or not. If the rocks of the district be highly jointed and pervious, we are unlikely to succeed; but if they be less fissured, there is some hope of reaching the water-level at a moderate depth. It is needless, however, to say that much will depend upon the climatic conditions of the region, for the position of the water-level is necessarily largely determined by the rainfall.

The superficial accumulations of this and many other countries not infrequently contain large quantities of water, either derived directly from the rainfall or introduced into them by natural springs—while in other cases, it has filtered into them from streams. Sheets of sand, for example, which are underlaid and perhaps overlaid by impervious clay, usually hold water. Again, the recent alluvia of our rivers, and the more ancient flats and terraces of similar materials which occur so frequently at various levels in our valleys, may yield copious supplies. The water obtained from the younger alluvia has obviously percolated into them from the adjacent stream or river. The older alluvia, on the other hand, have usually derived theirs from the valley slopes—a very superficial supply—but now and again the water flows into them from true springs issuing into or underneath the deposits. Common wells, dug in superficial deposits of the kind referred to, not infrequently yield a good supply of potable water, but they are not always to be trusted. Near towns and villages, and even in the vicinity of isolated dwellings, they are liable to contamination, impurities being readily filtered into them, especially during wet seasons. The wells sunk in an old river-terrace may, under ordinary conditions, yield excellent water, more particularly when the parent source of the supply is a spring discharging into the deposits. In times of heavy flood, however, when the adjacent river rises to the level of the terrace, the gravel is rapidly saturated, and impurities may be washed into the wells. The fact that when the rivers are in flood, outbreaks of typhoid fever often occur in riparian districts supplied from such wells is sufficiently suggestive. The water, which under ordinary conditions is quite wholesome and suitable for all domestic purposes, is, perhaps, never suspected, and may continue to be used until the next considerable flood repeats the work of its predecessor.

In certain districts deeply covered with loose deposits of gravel, sand, clay, etc., it is often difficult or practically impossible to sink common wells for a local water-supply. When such is the case, engineers often have recourse to **driven wells**. These are made by forcing down a strongly pointed iron pipe, pierced with holes round the bottom to admit the water. The advantages of this system are obvious, for not only can the pipe be driven to depths much below those reached by any ordinary well, but the water-supply obtained is protected from impurities coming from the surface. In populous districts, however, even driven wells may in time become polluted, for the pipe, subject to the corrosive action of foul liquids descending from the surface, may eventually yield admission to the enemy.

When good springs are not available, common wells are often the only source of supply in country districts. In sinking these it is always advisable to take the geological conditions into consideration. Remembering that underground water finds its way in the direction of dip, care should be taken to sink wells in such positions that impure surface water cannot reach them by percolating along the bedding-planes. It is absolutely necessary, moreover, that wells should be placed as far away as possible from dwelling-houses, cesspools, drains, etc., and every possible source of pollution. Frequently, indeed, it may be found necessary to line them with water-tight walls, especially in the case of wells that are sunk in more or less unconsolidated deposits. Even after every precaution is taken, however, no surface-well can be considered perfectly safe—although there are some obviously more liable to be contaminated than others. Wells sunk in river alluvia, in proximity to and upon the same level as dwelling-houses, are the most dangerous of all.

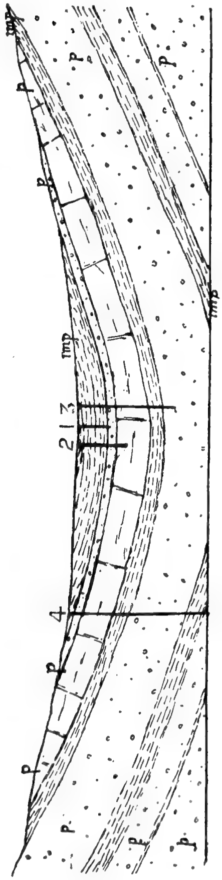


FIG. 136.—ARTESIAN WELLS.

Artesian Wells.—The driven wells referred to above are often true artesian wells on a small scale, for an artesian well is simply a borehole sunk to some permeable stratum in which the water is under such high pressure that when it is reached it rises towards the surface—the upper limit reached by it being determined by the height of its head or source above the mouth of the well, and the amount of frictional resistance it has to overcome. Should the latter be very great, there may be no rapid rise of water in the well. The rock may be porous enough in texture, but if it be not traversed by more or less open joints and fissures, the hydrostatic pressure may barely suffice to keep up a gentle circulation. Fortunately, such planes of division are seldom or never absent, and in certain rocks, as we have learned, they are often relatively wide and open.

The accompanying diagram (Fig. 136), will serve to indicate the geological conditions under which an artesian water-supply is obtained. The section is supposed to be taken across a broad area, throughout which the strata, consisting of pervious (*p*) and impervious (*imp*) beds, are arranged in a basin-shaped form. Rain falling on the outcrops of the pervious beds which are overlaid and underlaid by impermeable strata, percolates in the direction of the bedding-planes, and accumulates until each porous stratum becomes saturated up to its outcrop. It is obvious that this imprisoned water must be under hydrostatic pressure, which necessarily increases with the depth and reaches a maximum in the centre of the basin. Were a boring made at 1 through the uppermost impervious stratum into the subjacent water-logged bed, an uprush of water to the surface would ensue. At first, the water might form a tall fountain—the height of which would be determined not only by hydrostatic pressure, but by the amount of frictional resistance to be overcome by the water. If the passage of the water through the porous bed were favoured by open fissures, the fountain might reach a height not very much below that of the outcrop of the bed. Shortly, however, it would begin to decrease in height until it reached a level determined by the average rainfall of the district. It would, in fact, behave like a perennial spring. A boring sunk at 2 would tap a deeper stratum, and cause a still stronger outflow owing to the greater head; while the beds tapped by 3 and 4 would for a similar reason send yet more powerful uprushes of water to the surface.

The geological conditions represented in the diagram are, of course, ideal. Each pervious stratum is supposed to retain all the rain-water which soaks into it at its outcrop. In point of fact, however, such conditions rarely if ever do obtain. So-called impervious strata are only relatively non-porous, while continuous joints and other lines of fissure, traversing all the beds of a series alike, are so seldom absent, that the water in deeply buried pervious beds must in less or greater degree escape towards the surface. Hence, when an artesian well is sunk, the water does not always rise so high as might have been anticipated, even after allowance has been made for frictional resistance. It must not be supposed that a basin-shaped arrangement of the strata is essential for the formation of artesian wells. Any series of impermeable and permeable beds dipping continuously in one direction for some considerable distance, may contain abundant supplies which, under certain conditions, can be reached by boring. Some of these conditions may therefore be briefly considered.

A well-jointed porous bed, or series of beds, underlaid and overlaid by impermeable strata, may thin-out gradually in the direction of dip, and when such is the case they become water-logged (Fig. 137). Or the descent of water along the bedding-planes may be interrupted, not by the thinning-out of beds, but by such barriers as have already been referred to—faults, dykes, and other discordant junctions. Or, in the absence of any underground dams, the descending water may be stopped at extreme depths by the increasing temperature — the hydrostatic pressure being eventually counterbalanced by the tension of superheated steam. It is under such conditions as these that many natural springs originate—the imprisoned water seeking to escape pressure tends to rise through joints or other lines of weakness towards the surface. Sometimes, however, it is prevented doing so, or is only partially successful, and immense stores are thus often retained underground. Such hidden sources are not difficult to discover, especially in regions the geological structure of which can be readily ascertained from a study of the rocks exposed at the surface.

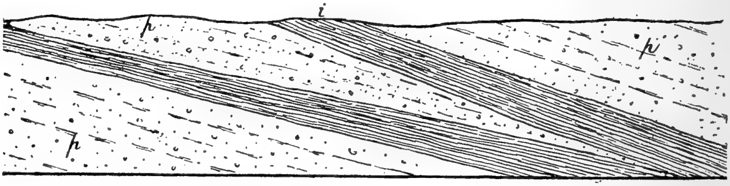


FIG. 137.—WATER-BEARING BEDS WEDGING OUT DOWNWARDS.

The more important points to be considered in the search for an artesian water-supply may be summarised as follows:—

1. Having ascertained that the strata over a wide region have a dominant dip in one direction, we must endeavour to acquire as complete a knowledge as possible of the various rocks and rock-groups. It is essential for success that pervious beds should occur interstratified with impermeable strata, the best kinds of water-bearing beds being sand and

gravel, sandstone, grit, conglomerate, and highly fissured limestones.

2. The thickness of the entire succession of strata should be carefully measured, and the precise position in the series of any water-bearing beds should be ascertained.

3. It is, further, most important that the average angle of dip should be determined, otherwise we shall be unable to estimate the depth from the surface at which the water-bearing beds may be expected to occur at any given point.

4. The inclination of the strata must not be too great, for obvious reasons:—(*a*) Gently inclined strata have relatively broad outcrops, and therefore are in a position to absorb more rain than if they had been highly inclined or vertical. Thus, the outcrops of a series of strata, 100 feet thick, dipping at an angle of 1°, would be rather more than a mile in width; while, if the angle of dip were 5°, the width of outcrop would be only 350 yards or thereabout—the width necessarily varying inversely as the dip; (*b*) With an inclination of only 1°, a stratum descends about 30 yards in a mile; but a dip of 5° carries it down 147 yards in the same distance; while at angles of 10°, 20°, and 40°, the depths at which the stratum would occur would be about 300, 630, and 1490 yards respectively. It is obvious, therefore, that with a high dip a water-bearing bed must within a short distance descend to a greater depth than the engineer might consider it possible or desirable to bore.

5. Let us suppose, however, that we have assured ourselves that the character of the strata is quite satisfactory, and that their inclination is equally favourable; we have still to ascertain whether the region is traversed by faults, dykes, or other discordant junctions which may serve as subterranean dams. It is quite obvious that, if any such obstructions occur, their position must influence the engineer in selecting a site for an artesian well. It would be hopeless to bore for water on the dip-side of a strike-fault or a dyke following approximately the same direction, whereas a boring put down on the rise-side would in most cases be successful.

6. When the strata consist throughout of pervious beds—such as sandstones, highly cleft limestones, etc.—the chances of obtaining an artesian water-supply are much diminished,

Nevertheless, even in such cases, there will in all probability be some closer grained or relatively impervious bed or beds to stay the downward passage of the water. An extended survey of adjoining districts may even show that the pervious beds, as they range beyond our region, are underlaid by or interosculate with impervious beds; or that, in the direction of the dip, they are eventually interrupted by faults, dykes, or other barriers, and may not, therefore, be so barren of water at a moderate depth as appearances in our own neighbourhood might have led us to infer. Should the whole area be more or less deeply mantled with impervious superficial accumulations, such as boulder-clay, the prospects of obtaining water by boring would be considerably increased.

7. It goes without saying that the water obtained from a bore-hole, although sufficiently abundant, may yet be unsuitable for the purpose the engineer has in view. A careful survey of the catchment area should, therefore, be made preliminary to any boring. It may be that some of the pervious beds contain deleterious ingredients, which must unfavourably affect the quality of the water; while, at other horizons, water-bearing strata of a satisfactory character occur. Should it be necessary to pass through an undesirable source of supply to reach a more promising source at a lower level, the water coming from the higher level can be prevented from contaminating that of the lower level, by simply tubing it off. Another danger is the infiltration of foul liquids from the surface. These may not penetrate sufficiently far to affect the water at the relatively deep level from which it is drawn. But unless the bore-hole is properly tubed for some distance down from the surface, it is likely enough to be invaded by pollutions.

Drainage.—In planning a scheme of drainage either for town or country, it is not enough to consider only the natural slope of the ground, and the ease with which the waste products of a community can be discharged elsewhere. It must be remembered that the external configuration of the ground may not coincide even approximately with the internal or geological structure. The surface may slope in one direction and the subjacent strata in quite another. There is always a danger, therefore, of polluted liquid finding its way down the bedding-planes, and poisoning the underground water-supply of adjacent districts. It is, of course, often necessary to carry drains in some given direction other than that which geological considerations might dictate—for questions of safe outlet and the expense of excavation cannot be ignored. In cases of this kind, all the engineer can do is to see that the drains are made as water-tight as may be, and to insist on the closing of every common well in the immediate neighbourhood. Flat lands in the neighbourhood of considerable towns are sometimes laid out as sewage-fields, with satisfactory results, it may be, to the towns, but often much to the prejudice of a scattered rural population, whose water-supply may come entirely from common wells. Whatever excuse there may be for carrying the drainage of a city in some particular direction, irrespective of geological considerations, there can be none for discharging sewerage over the surface of the ground without preliminary inquiry as to what may happen in the event of leakage into the rocks below. Cases could be cited to show how neglect of this precaution has been followed by disastrous results. Some low-lying fields were selected by a certain town for sewage irrigation. The subsoil was boulder-clay, a deposit supposed by the engineers to be impervious. But there are boulder-clays and boulder-clays; many are practically impermeable, others are only relatively so. This particular boulder-clay was one of the latter class, somewhat sandy in texture, and only two or three feet at most in thickness. Unfortunately, also, the sewage-field spread over the back of a low anticlinal arch. Under those conditions the inevitable result followed in due time. In a year or so the subsoil of boulder-clay become water-logged, leakage took place into the underlying strata, and the foul liquid made its way down the bedding-planes and poisoned all the springs and common wells in the surrounding neighbourhood—typhoid fever, of course, ensuing.

In villages and rural districts, where no general system of drainage is provided, cesspools are often sunk. When these are carried down through a thick bed of clay into underlying gravel and sand, they may suit the purpose of their owners well enough. It is obvious, however, that they are a menace to the neighbourhood, and that, in time, springs and common wells may become polluted. This primitive kind of drainage is only permissible in new countries where the population is sparsely scattered. They should not be tolerated in a populous region that is dependent for its water-supply on wells and springs, without the most careful inquiry into the geological conditions.

Low-lying lands with a very gentle slope are often cold and wet, or even swampy and boggy. Surface drains in such cases may be quite useless, owing to the low gradients. Very often it is the presence of an impermeable hard pan at the depth of a foot or two below the surface, which prevents the escape of the water. With the breaking-up of this " pan," the superficial water filters into underlying porous beds, and the land is at once improved. Occasionally, the barrier to the escape of superficial drainage is more deeply seated, and may be due to the occurrence of some thick impervious stratum of clay, shale, etc., either occupying the surface or appearing immediately underneath overlying porous beds. In such a case, if no outlet can be obtained by surface-draining, it is sometimes possible to sink pits or to bore through the impermeable stratum into underlying beds which are porous, and through which the superficial water eventually drains away.

Distribution of Disease in Relation to Geological Conditions.—Some writers have adduced statistics to show that certain diseases are more or less closely associated with particular geological systems. This supposed connection between groups of rocks and the diseases that afflict the folk who reside upon them, is due rather to the physical conditions of the regions where those rocks are prevalent than to the rocks themselves. The connection, if there be any, is not direct, but indirect. In most cases it will be found that the more immediate causes of such distribution of disease are (*a*) the *water supply*, and (*b*) the *physical conditions*, more especially those which affect the force and direction of the winds. Many diseases, as everyone knows, arise from the free use of contaminated water. Some water, again, may not be polluted by sewage, and yet contain an excess of inorganic matter (as lime, magnesia, iron-oxide, etc.) in solution, or, on the other hand, there may be an insufficient quantity of mineral ingredients present, as in the case of water derived from melting snow or ice. Other districts may be unhealthy owing to the undrained character of the land. It is matter of common knowledge that damp, cold soils favour many diseases. Even in one and the same district, we may note that houses built on dry rock are healthier residences than others in their proximity which are founded on damp ground. Once more, the topographical conditions of a district necessarily influence the climate and affect the health of a community. It has been found, for example, that a high rate of mortality prevails in districts which are exposed to the full force of the winds sweeping inland from the sea, the mortality being largely due to phthisis.

If, therefore, it be ascertained that the occupants of some particular geological area are more subject to certain diseases than the denizens of another where the prevailing rocks are of a different kind, we need not credit the rocks themselves with having any direct influence on the life of man. In most cases it will be found that districts are unhealthy either because of insufficient drainage, or the water-supply will be to blame, or it may be that the topographical conditions do not afford sufficient protection from the full force of the wind.

CHAPTER XXIV

SOILS AND SUBSOILS

Agents of Disintegration ; Insolation and Deflation ; Rain ; Frost ; Life. Weathering of Rocks. The Soil-cap. Classification of Soils—I. Bed-rock Soils, their Varied Character ; Soils derived from Igneous, Metamorphic, and Derivative Rocks. II. Drift Soils ; Glacial, Alluvial, and Æolian Soils.

Rock-disintegration.—Subsoil has already been defined as an unconsolidated heterogeneous aggregate of disintegrated rock material, and soil as essentially the same, with the addition of organic matter. Both are the result of the operation of various epigene agents, and are therefore properly included among *derivative rocks.* Everywhere throughout the world we meet with these superficial accumulations. As might have been expected, they vary in character according to the conditions under which they have been formed, and the nature of the rocks from which they have been derived. In some regions, for example, they consist largely of angular and subangular detritus, while in other places they may consist mainly of sand or of clay, as the case may be. In high latitudes and in mountainous lands the soil-cap is usually very stony; in lower latitudes and over plains and gently undulating tracts its ingredients are commonly finer grained. In most regions, however, arable soils are composed essentially of insoluble quartz-sand and clay, in ever-varying proportions, throughout which are disseminated larger or smaller percentages of organic matter and of certain more or less soluble ingredients, such as iron-oxides, magnesia, lime, soda, potash, etc.

In preceding pages, frequent reference has been made to the alterations and transformations of minerals and rocks induced by epigene action. Again, while dealing with the structural phenomena of derivative rocks, we have briefly considered the various origin of sedimentary deposits. The remarks that follow, therefore, may be taken as a kind of summary of much that has already been advanced on the subject of rock-disintegration, illustrated by special reference to the geological origin of soils and subsoils.

Insolation and Deflation.—Among the various agencies that tend to disintegrate rocks, and to form a soil-cap, are changes of temperature. Rock-surfaces are heated by day and in summer time—cooled at night and during winter. They thus alternately expand and contract, and this leads to disintegration, for their constituent minerals often yield unequally to strain or tension. Such is notably the case with rocks composed of minerals differing in colour, density, and expansibility, such as granite, gneiss, diorite, etc. Even in the case of homogeneous rocks, it is obvious that alternate heating and cooling of the surface must give rise to strain and tension. In countries like our own, where there is no great diurnal range of temperature, any rock-changes due to this cause alone are hardly noticeable, since they are masked or obscured by the action of other and more potent agents. But in the rocky deserts of tropical and subtropical regions, bare of verdure and practically rainless, the effects produced by alternate heating and cooling, or "insolation" as the process is termed, are very marked. The rocks are cracked and shattered to a depth of several inches; the surfaces peel off and are rapidly disintegrated and pulverised. Wind then catches up the loose material and sweeps it away, leaving fresh surfaces exposed to the same destructive action. More than this, the grit, sand, and dust carried off by the wind are used as a sand-blast to abrade and erode the rocks against which they strike. In this manner cliffs and projecting rocks are undermined, and masses from time to time give way and fall to the ground, where, subject to the same grinding action, especially towards the base, they tend to assume the appearance of irregular blocks supported upon pedestals. "Deflation," or the transporting action of the wind, goes on without ceasing, with the general result that the whole surface of a rainless region tends to be gradually lowered, the loose materials travelling outwards from the scene of their origin to the borders of the desert.

Action of Rain.—Even in countries like our own, insolation and deflation doubtless share in the disintegration of rocks and the transport of the loosened materials. Undoubtedly, however, in these latitudes, the most conspicuous agents employed in the work of reducing rocks to the condition of grit, sand, and clay, are rain and frost. Rain always contains some oxygen and carbonic acid absorbed from the atmosphere, and after it reaches the ground, still larger stores are derived by it from the decaying vegetable and animal matter with which soils are more or less impregnated. It is thus enabled to attack the minerals of which rocks are composed. In every region, therefore, where rain falls, soluble rocks, such as limestone, are gradually dissolved, while other kinds of rock are decomposed and disintegrated. In limestone areas it can be shown that sometimes hundreds of feet of rock have thus been gradually removed from the surface of the land. And the great depth now and again attained by rotted rock testifies likewise to the chemical activity of rain-water. This is particularly noticeable in warm-temperate, sub-tropical, and tropical latitudes, where felspathic rocks are not infrequently decomposed to depths of a hundred feet or more. In temperate and northern regions, the amount of rotted rock is rarely so great. The thicker rock-crusts of southern latitudes are supposed to be due to the larger supplies of acid derived from the more abundant vegetation. To some extent this is probably true, and there can be little doubt, also, that the chemical action of rain is facilitated by the higher temperature of those regions. There is another reason, however, for the relatively meagre development of rotted rock in northern countries generally. Those regions have, at a geologically recent date, been subjected to glacial conditions. Broad areas of temperate Europe and North America, for example, have been scraped bare by extensive ice-sheets, resembling those of Greenland and the Antarctic Circle. In more southern latitudes the rotted rocks have escaped such abrasion and denudation, and hence it is not strange that they should attain so great a thickness. The decomposed rock-material encountered in the northern parts of Europe and North America has been formed, for the most part, subsequent to the disappearance of glacial conditions; while in southern regions, rock decay has gone on without interruption ever since those lands came into existence.

Action of Frost.—The disintegrating action of rain in temperate and high latitudes is greatly aided by frost, and the same is the case in the elevated tracts of southern latitudes. Rain renders the superficial parts of rocks more porous, and thus enables frost to act more effectually; while frost, by widening pores and fissures, affords readier ingress to meteoric water. Water freezing in soils and subsoils, and in the interstitial pores and minute fissures of rocks, forces the grains and particles asunder, and when thaw ensues, the loosened material is ready to be carried away by rain or melting snow, and subsequently, it may be, by wind. The same process takes place on a larger scale in the prising-open of joints and bedding-planes, and the consequent rending asunder of rocks. This action is best seen in Arctic regions and at high levels in our own and other countries, where the solid rocks not infrequently become buried underneath their own ruins. By and by, however, these loose, angular fragments are shattered, crumbled, and pulverised by frost, until they are in a condition to be swept away by wind, rain, or melting snow. The solid rock then comes again within reach of the same destructive action, and so the work of disruption and disintegration continues.

Action of Plants and Animals.—The acids derived from decaying organic matter are powerful agents of chemical change. Without their aid, rain would be a much less effective worker. Living plants themselves, however, attack rocks, and by means of the acids in their roots, dissolve out the mineral matter required by the organisms. Further, their roots penetrate the natural division-planes of rocks and wedge them asunder; and thus, by allowing freer percolation of water they prepare the way for more rapid disintegration. Nor can we overlook the part played by tunnelling and burrowing animals, some of which aid considerably in the work of reducing rocks. Worms, for example, by triturating in their gizzards the stony particles of a soil, reduce these in size. They also play a most important part in soil-circulation. In soils which have long been undisturbed by the plough, coarse particles and stones are usually absent. This is obviously due in chief measure to the bringing up by the worms of fine soil from below, and its deposition at the surface as "casts," which are spread out by the action of rain and wind. Eventually, in this way, a more or less considerable stratum of fine soil accumulates, and gradually buries any stones that may have been lying at the surface. It must be remembered, however, that the transport of dust by wind is also an important factor in the formation of fine soil in many regions, and that the gradual burial of "ancient monuments" of one kind or another is probably, in many cases, largely due to the gradual accretion of wind-blown materials.

Weathering of Rocks.—We have now enumerated the more important epigene agents employed in the formation of soils and subsoils. As these several agents are often associated in their work, it is sometimes hard, or even impossible, to say which has played the dominant rôle in certain cases. It is obvious, however, that the disintegration of rocks is partly a mechanical, partly a chemical, process, and that the ultimate result of superficial action is to break up minerals and rocks into soluble and insoluble, or practically insoluble ingredients. Even the hardest and most resistant of rocks and rock-ingredients must succumb. Those that resist solution are eventually reduced by mechanical action to finely divided particles, which are readily transported by running water or carried on the wings of the wind. Some of the harder minerals, and notably quartz, may long survive the rock masses of which they once formed a constituent portion, and continue to play the same part over and over again. Here, for example, is a pebble of liver-coloured quartz picked up from a gravelly beach on the Firth of Forth. Whence has it come, and what tale has it to tell? Originally it formed a portion of some vein or layer traversing the metamorphosed rocks of the Scottish Highlands. Detached from its parent rock in Old Red Sandstone times, it was rolled down the bed of some torrential stream, becoming well rounded in the process, until it reached the shore of a great inland sea—the "Lake Caledonia" of geologists. Together with many boulders and pebbles of the same kind, and multitudinous rounded stones of other types of rock, it eventually became sealed up in the great conglomerate that forms the base of the Old Red Sandstone system in Central Scotland. Ages pass away — Lake Caledonia vanishes, and its conglomerates, red sandstones, etc., and igneous rocks, now forming part of a land-surface, are gradually denuded. The old conglomerate is largely broken up, and our liver-coloured quartz, again at liberty, becomes the sport of the waves upon a sea-beach of Carboniferous times. Reduced in size by constant attrition, but otherwise unchanged, it is eventually locked up in one of the numerous conglomerates of the period. What its history may have been throughout the vast æons which succeeded up to the close of Tertiary times, we cannot tell. Possibly it lay *perdu* during all that prolonged period in its Carboniferous bed. Or it may have been dug out at some distant date, and again played its part as a rolling-stone on sea-beach or river-floor. Eventually, however, it was enclosed in the bottom-moraine or boulder-clay of the great *mer de glace* that formerly overwhelmed all Scotland. In due time this *mer de glace* vanished, leaving its accumulations to be attacked and disintegrated in their turn. Nowadays, the boulder-clay is being eaten into by the sea, and our liver-quartz, once more set free, repeats its coastal wanderings, and for all that we can tell may yet survive to run through a similar cycle of changes again and yet again.

But quartz is an exceptional mineral, in comparison with which the great majority of rock-formers are ephemeral. Few of the numerous complex silicates with which it is associated in crystalline igneous and metamorphic rocks survive the process of disaggregation by which these gradually become broken up. Now and again the felspars, and even some of their ferromagnesian associates—all in a more or less altered state—may yet retain their individuality, and enter sparingly or more abundantly, as the case may be, into the composition of derivative rocks. In the case of *arkose*, for example, we have a rock derived immediately from the disaggregation of a granite, and consisting, therefore, of quartz, felspar, and mica, assorted and arranged by water action. The quartz may be more of less water-worn, and the felspar and mica not only worn, but to some extent chemically altered—nevertheless, each mineral has retained its individuality. In like manner, certain of the minor accessory ingredients of crystalline igneous rocks have often survived the demolition of their parent rocks, and are now and again met with as rolled pebbles and grains in sand and gravel. In such cases, however, the gravel and sand have usually been derived directly from the disintegration of the igneous rocks in question. Neither zircon, rutile, nor magnetite could survive the manifold vicissitudes through which grains and pebbles of quartz have passed. Sooner or later they lose their individuality, and are transformed.

Thus the process of rock-disintegration or "weathering," as it is termed, may be said to consist essentially in the breaking up of complex, and therefore usually unstable compounds, and the consequent production of simpler and more stable bodies. Hence, when igneous and schistose rocks are highly weathered, their complex silicates are transformed and converted into simpler compounds, some of which are soluble, while others are more or less insoluble. The soluble ingredients tend, therefore, to be leached out and washed away. The soil-cap formed upon such rocks, however, is rarely quite destitute of soluble matter. Even when the disintegrated materials have been transported by water and deposited elsewhere in the form of sand, clay, silt, etc., these sediments will usually retain a larger or smaller proportion of soluble matter—the process of disintegration and decomposition of the several constituents of the original or mother rock has not been completed. In short, sedimentary deposits, derived directly from the breaking-up of igneous masses, frequently contain a larger or smaller proportion of the relatively unaltered detritus of the parent rocks. We know, however, that many sedimentary rocks are built up of materials which have been used over and over again. Rocks of this kind, therefore, may consist exclusively of insoluble ingredients—the only soluble matter they may contain being the binding or cementing material introduced into them by percolating water. Repeatedly exposed to weathering—winnowed and rewinnowed again and again by wind or water, or both—sedimentary materials eventually come to form beds of pure quartz-sand and fine clay, composed of hydrous silicate of alumina alone, with, in most cases, some proportion of the finest quartz-flour—all soluble ingredients having been removed.

The Soil-cap.—If the soil-cap, therefore, consists essentially of disintegrated rock-materials, it is obvious that it must vary very much in character. In some places it will contain a high percentage of soluble matter—in other places it will contain little or none at all—and between these extremes all gradations may be expected to occur. The character of the soil-cap being thus dependent upon that of the underlying rocks, a good geological map might be expected to throw much light on the present distribution of soils. And so, indeed, it does; nevertheless, other factors have had their influence upon the distribution of soils, and unless these are kept in view, a geological map may be misleading. The colours upon such maps have reference, as a rule, only to the so-called "solid rocks," and these may or may not crop out at the actual surface. As a matter of fact, they are often deeply buried underneath superficial accumulations of gravel, sand, clay, loam, peat, etc. Wide regions may be represented on the map, therefore, as being occupied by limestone, or by sandstones and shales, or other strata—although none of these may actually appear at the surface—the only exposures being those seen in stream- and river-courses. All the intervening low grounds may be thickly mantled with superficial deposits. In cases of this kind, therefore, the soils take their character from the overlying deposits, and not from the covered and concealed bed-rock. It is hardly necessary to say that under such conditions the soil-cap may differ very considerably in character from that which the solid rocks would have yielded. Again, the actual configuration of the ground must influence the distribution of soil. All loose disintegrated rock material tends to travel downwards. Rain, alternate frost and thaw, etc., slowly or more rapidly, as the case may be, cause soil-ingredients to pass from higher to lower levels—thus the disintegrated materials derived from one kind of rock may invade and overlie the outcrops of, it may be, totally different strata. The character of a soil may even be very considerably modified by the action of the wind. In Central France, for example, wind blowing from east or south-east is laden with fine dust, derived from the disintegration of the volcanic rocks of Mont Dore and Cantal. This dust, therefore, contains many fertilising ingredients—notably potash and phosphoric acid. Brought down by rain and snow, it has appreciably increased the fertility of the soil of Limagne—each hectare of that region being estimated to receive 1000 kilos of dust per annum. But if wind in some cases adds to the growth of soil and influences its character, it not infrequently operates adversely. The plateau of the Karst, between Carniola and Istria, for example, is practically devoid of soil—the strong winds constantly sweeping it away from all tracts which are not protected by forests, or sheltered by the configuration of the ground. In like manner, the mountains of Provence are denuded of soil by the mistral.

Having recognised that all soils consist of disintegrated rock materials—derived either from immediately subjacent solid rocks or from more or less incoherent accumulations, under which the latter are often concealed, writers on agriculture have classified soils as *Sedentary* and *Travelled*, or *Transported.* The terms are not strictly appropriate, but they may serve their purpose so long as we understand them to have reference to the nature and source of the materials from which the soils have been derived. It might obviate confusion, however, if we substituted the term *bed-rock soil* for *sedentary soil*, and adopted the term *drift soil* employed by our Geological Survey in place of *travelled* or *transported soil.* We should thus have two tolerably well-defined classes of soil—one including soils derived directly from the bed-rock, and the other embracing every soil formed upon the surface of unconsolidated "superficial formations" of all kinds—whether glacial, alluvial, or æolian.

1. BED-ROCK SOILS

Under ordinary conditions the soil-cap covering the bed-rock shows the following succession:—

(a) *Vegetable Soil* or *Soil Proper.*—A layer of variable thickness, but seldom thinner than two or three inches, or thicker than nine or a dozen inches. Owing to the presence of organic matter, it is dark in colour. It may consist of fine-grained, or relatively coarse-grained materials, or of a mixture of both—its general character being necessarily determined by that of the underlying subsoil and bed-rock. Usually it is coarser in texture than the subsoil into which it gradually passes.

(b) *Subsoil.*—An earthy accumulation of quite indeterminate character and thickness, but commonly finer grained and lighter in colour than the vegetable soil. Fragments of the bed-rock are usually scattered more or less abundantly through the subsoil, but are most plentiful towards the bottom of the stratum, where they often form a kind of rough rock-rubble. The subsoil proper contains no organic matter.

(c) *Bed-rock.*—Just as the soil passes down gradually into the subsoil, so it is often hard to say where subsoil ends and "living-rock" begins. The upper part of the latter is often much fissured, earthy matter filling the cracks until, as these are followed downwards, they close up.

The character of the disintegrated materials constituting soil and subsoil naturally depends mainly upon that of the bed-rock. Should the latter be made up of relatively insoluble ingredients—say siliceous sandstone, quartzite, serpentine, clay-slate or other argillaceous rock—the soil-cap will differ but slightly in character from the bed-rock; it will consist simply of disaggregated rock-material which has undergone little or no chemical alteration. In such cases, the soil-cap is usually thin and meagre. On the other hand, if the bed-rock be granite or any other highly felspathic rock, it is generally more or less deeply decomposed. The rock-fragments and particles of the soil and subsoil are likewise highly altered, the subsoil sometimes attaining a thickness of a hundred feet or more.

As disintegration and alteration are continually in progress, the subsoil may be said to be always gaining on the bed-rock, just as the soil continues to grow at the expense of the subsoil. The soil itself, however, does not necessarily increase in thickness, for, owing to the action of rain and wind, its surface is gradually lowered, the finer particles tending to be washed down or blown away. For the same reason, coarser grained materials become concentrated in the soil, which thus tends to acquire a coarser and more open texture than the subsoil, more especially under moist climatic conditions. The rate at which a soil wastes away varies indefinitely. Where the ground is flat and thickly clothed with vegetation, there may be little waste, while, owing to the action of worms continually bringing up fine-grained materials to the surface, the soil may come to show a finer texture than the subsoil. Other things being equal, however, surface-waste naturally increases with the slope of the ground, and is greater when the soil is bare than when it is well carpeted with verdure. As absolutely flat ground can hardly be said to exist, surface-waste is everywhere in progress, on steep and gentle slopes alike. Slowly or more rapidly, as the case may be, disintegrated rock-material is continually being urged forward, and eventually finds its way into brooks and rivers. In this way the whole surface of the land is gradually lowered. How effective such action has been, may be illustrated by the occurrence upon plateaus and flat hill-tops, of rock-fragments derived from thick formations which formerly overspread those regions, but have now entirely disappeared. As an example, we may cite the "grey-wethers" or "sarcen-stones" that often occur in the soils of the Chalk Downs. These fragments of siliceous sandstone are the relics of certain Tertiary deposits, which at one time covered wide areas in southern and south-eastern England. During the slow growth and waste of the soil-cap the Tertiary deposits referred to have been gradually but persistently removed, the "sarcen-stones" (owing to their size and their insoluble character) being the only recognisable relics left behind. In this way, notwithstanding the persistence of a soil-cap through long geological ages, the whole surface of a country has nevertheless been lowered for many hundreds of feet.

The great variety of bed-rock soils may be illustrated by a short description of those met with on certain well-known types of rock.

Soils from Igneous Rocks.—The soils derived from the disintegration of igneous rocks necessarily vary in character. It will suffice, however, to cite a few typical examples.

Granite.—The weathering of this rock has already been referred to, and we have learned that of its three constituents quartz is practically insoluble, while the felspar and its ferro-magnesian associate (mica or hornblende) are more or less readily broken up and resolved into kaolin and certain alkalies and alkaline earths which tend to be washed away as bi-carbonates in solution. Under favourable conditions, therefore, the subsoil overlying granite consists of an aggregate of larger and smaller roughly rounded or sub-angular fragments, in all of which the felspar is more or less strongly kaolinised. These fragments are set in a gritty clay-like earth, usually reddish, brownish, or yellowish in colour, through which non-elastic scales of bleached mica may be plentifully scattered. Although the soluble carbonates tend to be leached out, yet a larger or smaller proportion is left behind, for the gradual decay of the rock-fragments and particles is continually setting free fresh supplies. The vegetable soil does not differ essentially from the subsoil; it is a gritty clay, often stonier than the latter, but more deficient, as a rule, in soluble ingredients, and showing few or no scales of mica.

Since granites vary in character, their soil-caps are not uniformly alike. Very coarse varieties necessarily yield stonier soils than the finer grained kinds; while the resulting clays often differ much in the proportion of soluble materials. The soil derived from granites containing hornblende and a notable quantity of apatite, may be expected to be charged to some extent, not only with potash and lime, but phosphoric acid. Much, however, depends upon the position occupied by the bed-rock. In the low grounds of non-glaciated regions, granite is often decomposed to a very great depth, and may give a soil capable of high cultivation. But, in our own country, the rock usually occurs at mountainous elevations, where the conditions for the formation of a persistent soil-cap are not favourable. Wind, rain, and melting snow, and the steep gradients of the surface, all conspire to prevent the accumulation of disintegrated rock-materials. The hill-slopes are covered with sheets of grit and rough gravel (=quartz); over the low grounds the clay may here and there accumulate, but the soluble materials are, for the most part, removed.

Granite may be taken as the type of the acidic felspathic rocks. Quartz-porphyries and rhyolites yield soils of much the same character—they are essentially clays with a larger or smaller percentage of sand (quartz) and not infrequently with a notable proportion of potash, magnesia, and lime. But, just as with granite, the character of the soil-cap is largely determined by the configuration of the ground and climatic conditions. In short, the soil-cap, according to circumstances, may be a fine sandy clay, or a mere rubble of sand, grit, and rock-fragments.

Basalt.—As granite is the type of the acidic igneous rocks, so basalt may be taken as representative of the basic series. The essential constituents of this rock, it will be remembered, are felspar and augite (usually with olivine), and generally a considerable proportion of magnetite (often accompanied by ilmenite). The rock commonly weathers to some depth, becoming so disintegrated that it may be readily dug with a spade. The resulting soil is a dark-coloured loam—the more notable constituents of which are clay, fine sand, iron-oxides, and varying proportions of the carbonates of lime, potash, magnesia, together often with traces of phosphoric acid, derived doubtless from the decomposition of apatite—a common accessory mineral in basalt as in many other igneous rocks. Where the surface conditions are favourable, basalt always yields rich soils of this character.

Diorite, Porphyrite, etc.—That large class of igneous rocks, the silica percentage of which is less than that of the granites, quartz-porphyries, etc., but larger than that of the basalts and their associates, yield soils of an intermediate character, which would be classed rather as loams than clays, and are often highly fertile. The diorites and porphyrites are essentially compounds of soda-lime felspar with various ferromagnesian minerals, such as hornblende, augite, biotite, etc. The rocks do not, as a rule, weather so readily as basalt, but this is not always the case, for now and again their decomposed crusts and débris can hardly be distinguished from disintegrated and decomposed basalt. Generally, however, the soil derived from these rocks of intermediate composition contains a less percentage of iron-oxide than basalt-soil, and is usually more clay-like. The subsoils, as one might have expected, are rich in lime derived chiefly from the felspar, but also to some extent from the ferro-magnesian constituents. Other intermediate rocks, as syenite, trachyte, phonolite, give subsoils that are richer in potash than lime.

Upon the whole, then, we arrive at the conclusion that excellent soils may be derived from the decomposition of igneous rocks generally, some of them so argillaceous as to be properly designated clay-soils, others of a fine loamy character, and yet others of intermediate character—but all under favourable conditions, being capable of high cultivation. The colour of the soils is lighter or darker, according as the parent rocks are poor or rich in iron-oxides. Probably, the most fertile soils are those yielded by the basic rocks (basalt, etc.), and some of the intermediate rocks (diorites and porphyrites), forming, as they do, dark loams, rich in the soluble ingredients required for the growth of plants.

Soils from Metamorphic Rocks.—The weathering of certain metamorphic rocks results in the formation of quite as deep and good soils as are yielded by igneous rocks generally. On the other hand, many of the schists and their associates supply only meagre barren soils. It will suffice for our purpose to note one or two examples.

Gneiss.—As this rock consists of the same mineral constituents as granite, it weathers much in the same way, and the resulting soil is similar—a gritty clay, which, according to the physical conditions, may or may not be fertile. At high elevations the soil is either a mere rubble of grit and stones or a thin clay, from which the soluble constituents have usually been removed. Under more favourable conditions, as regards elevation and climate, the same rock may be covered with a deep and fertile soil-cap.

Mica-schist.—This rock, composed of quartz and mica in variable proportions, often yields a good loamy soil, which in favourable positions would be highly esteemed by agriculturists. Unfortunately, in these islands it usually occurs at considerable elevations, where climatic conditions do not favour cultivation. Nevertheless, the fertility of the soil is evidenced by the character of the trees it supports—the coniferous forests grown upon the mica-schists of the Scottish Highlands being much superior in every respect to those which struggle for existence on the meagre gritty clay-soils derived from the granites and gneisses of the same region.

Amphibolites.—These rocks are essentially aggregates of amphibole (hornblende, actinolite), but many other minerals are often present. They yield dark loamy soils of excellent quality, quite similar in character to those of the diorites and basalts. The rocks, however, do not occupy large areas in Britain, and are practically confined to our mountain regions, where the conditions are unsuitable for agricultural purposes.

We have now mentioned some of the metamorphic rocks which naturally tend to yield good soils. There are a considerable number of the same group of rocks, however, which from their mineralogical composition could not be expected to supply fertile soils. Amongst these may be mentioned *clay-slate*, over which the soil is usually a cold, wet, sterile clay. Now and again, however, owing chiefly to the presence in the slate of felspathic and micaceous ingredients, the soil may be of somewhat better quality. Another very unfavourable rock is *quartzite*, the thin soil formed upon which consists chiefly of chips, splinters, and grains of the rock held together sometimes by a meagre ferruginous sand. *Serpentine*, composed of a somewhat intractable or relatively insoluble hydrous magnesian silicate, is not more favourable to the production of soil than quartzite, the thin soil yielded by it being notable for its infertility.

Between these relatively barren soils and the good soils which, under favourable conditions, tend to form upon gneiss, mica-schist, and amphibolites, there are soils of intermediate character met with in many regions of metamorphic rocks; such as those that occur above *granulite*, *marble*, *chlorite-schist*, etc. The soils in question necessarily vary much in character, for the mineralogical composition of the rocks themselves is by no means uniform. The soil overlying marble is usually a clay (coloured red, brown, or yellowish, from the presence of iron-oxide), which may contain little or no trace of calcium carbonate. Marble, however, is not infrequently charged with many "new" or "contact-minerals," such as amphiboles and micas, from the gradual decomposition of which in subsoil and soil carbonates of lime and magnesia may be derived. Granulite, on the other hand, yields a soil comparable to that derived from the decomposition of certain gneisses and mica-schists. The soils formed upon chlorite-schist are commonly thin, gritty clays, often somewhat dark in colour, but relatively infertile, although hardly so barren as the soils derived from serpentine, quartzite, or clay-slate.

Soils from Derivative Rocks.—These rocks consist, for the most part, of arenaceous and argillaceous materials; amongst them, however, are included many important calcareous rocks. No doubt there are numerous other kinds of derivative rocks, but inasmuch as the outcrops of these occupy very limited areas, they may be here disregarded. Sandstones, shales, and limestones are by far the most widely-spread of derivative formations.

Arenaceous Rocks.—The large majority of these rocks are quartzose, and they tend therefore to yield light soils, which are often not sufficiently retentive. But they show great differences in this respect, many containing larger or smaller percentages of argillaceous matter, and giving rise to loamy soils of excellent quality. Some white sandstones consist almost exclusively of quartz-grains, and owe their induration to compression alone. The soil formed upon a rock of this kind, it need hardly be said, will be a barren sand, incapable of tillage. Many sandstones, however, owe their induration to some cementing material that binds the grains together. The cement may be calcium carbonate, iron-oxide, argillaceous matter, or other substance. When such rocks are weathered, therefore, the nature of the cementing material necessarily affects the character of the soil. Again, it may be noted that, although quartz is the dominant ingredient of most sandstones, yet many other constituents are sometimes present. Thus sandstones immediately derived from the breaking-up of an igneous rock may consist to no small extent of felspar, mica, and other minerals in a more or less altered condition. Few sandstones, indeed, do not contain scales of mica, which are not infrequently so abundant as to impart a fissile structure to the rock. However plentiful these minerals may be in a sandstone itself, they are not often conspicuous in the overlying subsoil, and are usually completely wanting in the vegetable soil. It is obvious, therefore, that they must become decomposed, and that their soluble alkalies and alkaline earths are available for the support of plant life. Some sandstones contain so much argillaceous matter that their weathered materials form clay-like rather than loamy soils. Such is usually the case with the palæozoic greywackés, which are only much indurated argillaceous sandstones. The soils they yield are usually cold, retentive clays. Owing to the fact that these rocks occur, as a rule, in high-lying districts, their soils are seldom tilled. In low-lying districts, however, soils of the same origin, when they can be well-drained, are cultivated with success. Greywacké, it may be added, often contains much felspathic material, which, on decomposing, supplies alkalies and alkaline earths.

Argillaceous Rocks.—These naturally give clay-soils, but, owing to the variable character of the rocks, there are as many differences among clay-soils as among arenaceous soils. Some argillaceous strata contain so much sand, that the soil resulting from their disintegration might be classed among the loams or transition soils, being neither clays nor sands. Not a few clay rocks consist almost entirely of clay and quartz in the very finest state of division, all soluble ingredients being practically wanting. The soils formed upon these are, it need hardly be said, very infertile. Certain argillaceous rocks, on the other hand, may be largely charged with calcareous matter, and would be then termed marls, some of which yield excellent soils. It may be noted here, however, that the term *marl*, as used by some geologists, is misleading. Many of the so-called "marls" of the Old Red Sandstone, the Permian, and the Triassic systems contain no carbonate of lime, but are simply clays with a larger or smaller percentage of sand. As they occur interbedded with sandstones, the overlying soils usually assume the character of a "strong loam," forming what is one of the most fertile soils met with in these islands. Good examples are furnished by the famous "red soils" of East Lothian, Wales, and Cornwall, all of which overlie rocks of Old Red Sandstone age, and the somewhat similar soils ("red ground") yielded by the Triassic Keuper Marl of Cheshire and the Midlands. Clay-rocks in general, however, tend to give heavy clay-soils, which are nowadays seldom tilled, but kept in grass.

Calcareous Rocks.—An absolutely pure limestone would be incapable of yielding a soil. All limestones, however, do contain insoluble impurities, such as sand and clay, and the soils derived from them are thus usually either loams or clays. Good examples of such soils are those met with in the Chalk districts of England. They are usually reddish or brown in colour, and vary in character from stiff, retentive clays to calcareous loams. The soil-caps of those regions are naturally thickest in the valleys—the tops and steeper slopes of the hills showing little or no soil at all. In some places, however, the hills are capped with sheets of flint-gravel—the flints having been derived from the gradual dissolution of the chalk in which they were formerly embedded. Limestones all the world over yield similar reddish, yellowish, or brownish clays and loams—the colour being due to the presence of iron-oxides. The famous *terra rossa* of Southern Europe is a well-known example. As most limestones are traversed by joints which have been widened by the action of acidulated water, much of the insoluble red earth formed at the surface is washed by rain, and, in some cases, by melting snow, into these open fissures. Limestone regions, therefore, especially when relatively high, are apt to show a rocky surface, sparingly sprinkled with a thin clay-like or loamy soil.

2. DRIFT SOILS

Under this head, as already explained, may be grouped all soils which do not owe their origin to the direct disintegration of the bed-rock, but are the modified upper portions of glacial, alluvial, and æolian accumulations of every kind. The materials of which they are composed have been transported for shorter or greater distances.

Glacial Soils.—These soils are usually somewhat tenaceous clays, but vary considerably in character. They overlie accumulations of glacial origin, which may consist either of stony or essentially stoneless clays—the latter being usually laminated, while the former are commonly amorphous.

Boulder-clay or *Till* is the general term applied to the stony clays. These clays, being of subglacial origin, consist almost exclusively of crushed and comminuted rock. In other words, they consist of unweathered materials—differing in this respect from all clays of truly sedimentary origin. As a rule, these stony or boulder-clays are of a highly impermeable character, and consequently, the soil formed upon them is usually thin. The subsoil is also thin, and the materials of which it is composed show commonly little trace of weathering—the most notable change being the partial oxidation of ferruginous constituents. Thus, a blue-coloured boulder-clay may graduate upwards into a yellowish or brownish clay, two or three feet in thickness, overlaid by a few inches of a more or less stony, tenaceous clay-soil. It may be said in general terms that the colour and composition of boulder-clay are determined by the nature of the bed-rock upon which or near to which it lies. Thus, in a district where red sandstones predominate, the overlying boulder-clay is usually reddish and more or less arenaceous: where Carboniferous rocks prevail (light coloured sandstones, black shales, fireclay, ironstones, coal, limestone, etc.), the till is dull bluish-grey in colour, and often exceedingly tenaceous: when the dominant country-rock is chalk, the boulder-clay forms a dirty greyish-white marl. A good geological map, therefore, although it may not show the superficial formations of a country, is nevertheless often a reliable index to the average character of the boulder-clays. The general local character of the till, however, does not hold good throughout. If we follow the direction of ice-flow in a country like Scotland, we soon discover that there are limits to the local character of the till. Coming down the valley of the Tweed, for example, from the heart of the Silurian Uplands to the low grounds near Melrose, we find that, so long as we are in the region of greywacké and shale, the till is a fawn-coloured, tenaceous, gritty clay, crowded with angular and subangular fragments of the country-rock. As we leave the Silurian strata and enter the region of Old Red Sandstone, the till continues to be composed of the débris of greywacké and shale, although here and there fragments of the underlying red sandstones begin to appear. Continuing down the valley, red sandstone boulders become more and more numerous, while the colour and texture of the clay gradually change, as crushed and comminuted sandstone enters more and more largely into its composition. The majority of the stones and boulders, however, are still of Silurian parentage—doubtless due to the fact of their superior durability—the red sandstones being much more readily pulverised. The till continues to present much the same appearance after the region of red sandstone has been left behind, but gradually it loses its pronounced red colour as Kelso is approached, while fragments of certain igneous rocks, which crop to the surface above that town, begin to abound. From Kelso to the sea the prevalent rocks are brown, reddish, grey, and white sandstones, sandy shales, marls, etc. The overlying till, therefore, is a somewhat arenaceous clay, light brown as a rule, but here and there with a reddish tinge. The bulk of the finer grained materials of this till are of local origin, but the most conspicuous stones and boulders are still greywacké commingled with abundant fragments of the "Kelso trap-rocks," and other igneous rocks traversed by the old ice-sheet. Similar phenomena are encountered everywhere in regions where boulder-clay occurs. While it is true, therefore, that this accumulation has a more or less local character—and this is especially the case with its finer grained materials—yet it must be remembered that the till formed in one place tended to travel forward with the ice. In this way boulder-clay often came to be deposited upon bed-rock of a very different character from that of the region where it was actually formed. No small proportion of the stones, and even of the gritty and clay-like material of the till that covers the low grounds of a country, is often of more or less distant derivation.

It will now be readily understood that the soils yielded by boulder-clay are of very unequal character and value. The dark lead-coloured tenaceous till met with in many Carboniferous tracts gives a most ungrateful soil—a thin, cold, unctuous, sticky clay in wet weather; and in drought, hard and unyielding. In other places within the same geological area, the till has proved more kindly—owing chiefly to a larger proportion of comminuted sandstone, limestone, and igneous rocks. The red and brown coloured boulder-clay soils, however, are upon the whole the best. These consist mainly of pulverised red sandstone, and form strong loams, rather than clays. Chalky boulder-clays, composed chiefly of pulverised chalk, yield clay-soils from which the calcareous constituents have sometimes been largely removed.

The agricultural treatment of soils is a subject on which the geologist has no title to speak. He may, however, be allowed to point out the danger of deep-ploughing upon boulder-clay soils of all kinds. Undisturbed boulder-clay consists almost exclusively of unweathered materials—its mineral constituents are quite unaltered, and it is therefore in no sense of the term a subsoil. It plays the part, in fact, of unweathered "bed-rock." Owing to its impervious character, the subsoil and soil formed upon it seldom exceed a foot or two in thickness. Now and again, as in sandstone regions, it is somewhat more pervious, and covered, therefore, with a thicker soil-cap. In some boulder-clay tracts, indeed, the arable soil considerably exceeds a foot. It will be found, however, that these thicker soils have not been derived exclusively from the boulder-clay upon which they lie, but have in large measure been washed down by rain from adjacent slopes. This is shown not only by the unusual thickness of the soil in question, but by the fact that it contains relatively few stones, while the much thinner soils of the neighbouring banks and mounds are crowded with stones, the tops of the banks being not infrequently covered with a thick sheet of course shingle and boulders.

Stoneless Clays.—These deposits consist usually of very fine gutta-percha clays. They are generally well laminated, and are confined in these islands to maritime districts, where they seldom occur more than 130 feet above the sea-level. They are best developed in the lower reaches of the great valleys of Central Scotland, where they form a considerable proportion of the Carse-lands of the Tay, the Forth, and the Clyde. Clays of precisely the same character are met with in the Newcastle and Durham districts. The deposits have occasionally yielded shells of Arctic molluscs, and now and again an isolated stone or boulder appears: in a few places, indeed, small and large erratics are of quite common occurrence, but that is exceptional. The clays are obviously of marine origin, deposited at a time when Arctic climatic conditions obtained. When carefully examined, they prove to consist for the most part of minute particles of rock and mineral, which, as a rule, are as fresh and unaltered as the similar fine ingredients of boulder-clay. When thoroughly washed and sifted, the clay yields an exceedingly fine rock meal or flour, of which the most abundant constituent is quartz. True clay or kaolin is of subordinate importance, but appears to be rather more abundant than in most true boulder-clays. These stoneless clays, therefore, would appear to be of the same origin as the former—they are the result of glacial grinding, and, unlike ordinary alluvial clays, are not the product of the mechanical and chemical process of weathering. They represent the fine mud, etc., swept into our estuaries by turbid rivers escaping from large glaciers, and too short a time elapsed before they settled down, to allow of much chemical alteration. It need hardly be said that the soils met with upon such clays are peculiarly tenaceous, except where, as sometimes happens, thin layers and bands of sand are intercalated in the upper part of the deposits. Deep-ploughing upon these clays is obviously not less to be avoided than in the case of true till.

Alluvial Soils.—Under this head we include all superficial deposits consisting of disintegrated and weathered rock-materials, which have been transported and spread out by water. Some of these formations have been accumulated in fresh water, others have been laid down in estuaries and upon the sea floor. They and their soil-caps naturally vary much in character. The coarser deposits consist of water-worn shingle and gravel, and are generally barren, owing to the rapidity with which rain is absorbed. Any soil formed at the surface tends in this way to disappear. Now and again, however, when the interstices between the stones are well filled with grit and sand, a light porous soil is formed. Between such coarse accumulations and the finest deposits of mud and silt, we meet with all gradations. Of the sands, quartz is the dominant ingredient, and a pure quartz-sand, it need hardly be said, cannot furnish a good soil. Many sands, however, contain larger and smaller percentages of clay, and may form loamy soils of excellent quality. From loams capable of high cultivation, we pass on to clays, many of which are tenaceous, although few alluvial clays have the tenacity so characteristic of the tills and stoneless clays of glacial origin. Alluvial clays and muds often contain much organic matter, and are frequently rich in soluble mineral salts. As examples of alluvial formations may be mentioned the flats and terraces of our river valleys, the great Carse-lands of Middle Scotland, the raised beaches of our maritime tracts, and the many patches of level ground which indicate the sites of former lakes. Under the same head, also, we may include the fluvio-glacial heaps and sheets of gravel, sand, etc., shortly described in Chapter XX. Although these deposits are primarily of subglacial derivation, yet their materials must obviously have been more or less altered and disintegrated while they were being transported and distributed. Moreover, their highly permeable nature has allowed the free passage of rain, so that in time all such fluvio-glacial gravels and sands have acquired much the same character as the similar deposits formed by ordinary river-action.* From an agricultural point of view, therefore, they may be included under one and the same head.

In fine, it will be understood that the chief distinction between "alluvial-formations" and those which have been described under the head of "glacial soils," is simply this, that the former consist essentially of "weathered" rock-material, while the latter are composed almost exclusively of "unaltered" mineral matter—of crushed, pounded, and pulverised rock, which had previously undergone little or no chemical alteration. The "alluvial formations," in a word, consist of disintegrated rock-material, and are true "subsoils." Glacial clay-deposits, on the other hand, are not "subsoils," but, properly speaking, unaltered "bed-rock."

---

* It may be noted, however, that the stones of a fluvio-glacial gravel are usually fresher than those of modern alluvial deposits. Their weathered crusts are thinner, and they are sounder internally. This is most notable in the case of basalt and similar rocks. When the stones of a modern gravel-bed have been derived directly from till, however, they are usually quite as sound as those occurring in a fluvio-glacial deposit.

Æolian Soils.—The most notable æolian accumulations are the *sand dunes* of maritime districts and certain inland areas. As the dominant ingredient of all dunes is quartz, they can hardly be said to yield a soil. Nevertheless, certain sand-loving plants find sustenance upon them, and succeed in binding the loose grains together, so that eventually some amount of humus is accumulated, and a thin soil is formed. But if æolian sand accumulations yield very poor soils, such is not the case with certain other wind-blown formations. The fine *dust* swept by the wind from desiccated regions, and distributed over adjacent tracts, may not only add to the fertility of soils, but under certain conditions may accumulate to such an extent as to conceal all bed-rock and native soil-caps over extensive areas. There can be little doubt that desert-dust has added to the fertility of the Nile Valley, while, according to Baron Richthofen, the massive sheets of *loess* which cover enormous tracts in China are true dust-deposits, gradually accumulated by the winds flowing outwards from the desiccated regions of Central Asia. In Europe, a similar deposit occurs in the Rhine Valley and in the low grounds traversed by the Danube, while the extensive sheets of "black-earth" forming the great plains of Southern Russia are also a variety of loess. The origin of the European loess has been much discussed, but it seems to be now the general opinion that the materials of the loess were, in the first place, of glacial and fluvio-glacial origin. The fine sand and clay that resulted from glacial grinding appear to have been introduced to the low grounds of Europe largely by the flooded rivers and inundations of the Ice Age. It is thought, however, that wind also played an important part in the transport of these fine-grained materials. Northern Europe covered with an ice-sheet must have formed an area of high-pressure, from which strong winds would flow southwards. During the severe winter season, all the streams and rivers would be reduced in volume, and wide areas, no longer inundated, would be exposed to the disintegrating action of frost. The fine fluvio-glacial deposits thus pulverised would be ready to be swept up by strong winds, and distributed over wide areas in Central and South-eastern Europe. Similarly, the fluvio-glacial accumulations of the low grounds, dried and desiccated, would in like manner tend to drift before the wind. In some such way, deposits originally of glacial and fluvio-glacial origin have been rearranged and redistributed by æolian action. This conclusion is supported by the occurrence in the loess of the remains of a true Steppe-fauna—embracing jerboas, pouched marmots, tailless hare, little hamster rat, and many other forms which are the common denizens to-day of the Steppes of Eastern Russia and Western Siberia.

Loess may be described as a fine calcareous loam, consisting of an admixture of minute particles of quartz and clay. The percentage of calcium carbonate varies, often reaching or even exceeding 30 per cent. Its light red or yellowish colour is due to the presence of iron-oxide. Small percentages of magnesia, potash, soda, and phosphoric acid are usually present. Loess thus yields an excellent soil, the regions covered by it being noted for their great fertility.

CHAPTER XXV

GEOLOGICAL STRUCTURE AND SURFACE FEATURES

Denudation and the Evolution of Surface Features. Mountains classified according to Structure and Origin ; Original or Tectonic Mountains —their Erosion and Transformation ; Subsequent or Relict Mountains. Plains and Plateaus of Accumulation and Erosion. Original or Tectonic and Subsequent or Erosion Valleys. Basins.

THE student of structural geology soon learns to recognise the importance of denudation. Almost everywhere he is confronted with evidence to show that enormous masses of rock have been removed from the land. He is prepared, therefore, to believe that erosion must have played an important part in the production of surface features. As his observations extend, he begins to realise that the configuration or shape of the land largely depends upon the lithological character and the geological structure of the underlying rock-masses. So constantly does this remarkable relationship appear, that it cannot be merely accidental. In regions which have been highly disturbed within late geological times, it is doubtless true that the larger or more prominent features of the land are the direct result of deformation. We see certain great mountain chains, the geological structure of which compels us to believe that they are simply wrinkles or flexures of the earth's crust. But in other lands which have not been subject to crustal deformation for a prolonged period of time, we can seldom trace any coincidence between surface features and underground structures. The mountains do not correspond with anticlinal folds—the valleys do not lie in synclinal troughs. The relation between the configuration of the ground and its internal structure is therefore not direct. In a word, observation has conclusively shown that in all highly denuded lands the forms assumed by the surface have been determined mainly by the character of the rocks and the mode of their arrangement. Hence it may be said, in general terms, that when a region is exposed to denudation, its relatively "soft" rocks and weak structures will be reduced more rapidly than its relatively "hard" rocks and strong structures, the latter coming in time to dominate the former in a more and more pronounced degree.

To sum up, we may conclude that many prominent features of the land are directly due to deformation of the crust, and that others are the immediate result of denudation and accumulation, while, between these two groups of land-forms, we recognise an intermediate type in the production of which both hypogene and epigene forces have been concerned. A glance at the structure and origin of the leading surface features of the land may suffice to make this clear.

I. MOUNTAINS

There are only two great classes of mountains. One of these comprises every height which owes its origin either (*a*) to the heaping-up of materials at the surface of the earth, or (*b*) to subterranean action, which has resulted in the deformation of the earth's crust. These two groups form the great class of *Original* or *Tectonic Mountains.* The second great class includes a vast variety of heights of quite a different origin. They have not been built up by accumulation, nor upheaved by crustal movements, but are simply the surviving remnants of ancient high lands. They now form mountains because the land masses by which they were at one time encompassed have gradually been worn down and removed. Lofty plateaus, for example, have been so deeply excavated by superficial action, that they have frequently lost their plateau character and acquired quite a mountainous aspect. Mountains of this kind we term *Subsequent* or *Relict.*

I. ORIGINAL OR TECTONIC MOUNTAINS.—These include two groups, namely, *Accumulation Mountains* and *Deformation Mountains*, of which the latter is by far the more important.

(*a*) **Accumulation Mountains.**—We need not dwell on the phenomena characteristic of this group. It is typically represented by volcanoes, the structure and origin of which are familiar. Volcanoes may occur singly or in irregular groups, or they may be distributed along definite lines or zones. They vary in size from mere monticles up to vast cones. Sometimes they appear in low-lying regions, at other times they occur upon the flanks or are strung along the crests of lofty mountain ranges. Built up, as they are, of materials ejected from below—of molten rock alone, or of loose stones, dust, and ashes alone, or, as is most frequently the case, partly of one and partly of the other—they all have essentially the same structure. They consist of successive layers of variable thickness, sloping outwards in all directions from the centre or centres of eruption. The actual form of a growing cone depends very largely upon the nature of the materials of which it is composed. Thus a volcano which emits highly fluid lavas does not, as a rule, throw out loose materials in much abundance. Hence such volcanoes have usually the form of more or less depressed cones—the liquid lavas flowing away and spreading out rapidly, while the limited supply of loose ejecta does not favour rapid growth in the vicinity of the crater. Viscous lavas, on the other hand, do not flow so rapidly, and tend, therefore, to coagulate at no great distance from the focus of eruption. And as they are generally accompanied by abundant discharges of loose ejecta, the resulting cone is usually more or less abrupt. Hence, in the case of active volcanoes, the external form is an expression of the internal or geological structure.

Volcanoes are subject, like all other portions of the land-surface, to the modifying influence of the superficial or epigene agents of change. While in a state of activity they are worn and degraded by rain and torrents, by which they are often deeply scarred and furrowed. But such ravages are more than compensated for during times of eruption and accumulation. When volcanic action ceases, however, there can be no such compensation—degradation then proceeds apace. The more or less steep inclination of the surface and the weak geological structure favour the action of the epigene agents. Gullies and ravines are rapidly deepened and widened; rock-falls and landslips ever and anon take place;

till sooner or later the symmetry of the original cone disappears. Undermined and breached in every direction, the mountain eventually loses the distinctive aspects of a growing volcano. After a prolonged period all that may be left projecting above the general level of the land may be the core or plug of igneous rock which cooled and consolidated in the funnel or pipe of eruption. Volcanoes, then, may be looked upon as typical "accumulation mountains," in which, while they are still growing, internal structure and external form coincide. No sooner are they extinct, however, than they begin to lose their characteristic shape, and a time at last arrives when there ceases to be any correspondence between structure and configuration.

But volcanoes are not the only examples of "accumulation mountains." Materials are heaped up at the earth's surface by other than subterranean action. Thus *dunes* owe their origin to the action of wind, while *moraines* are built up by glaciers. True, neither dunes nor moraines attain the dimensions usually indicated by the term *mountain.* The term, however, is rather popular than scientific, and in a scientific classification must be taken to include not only the loftiest elevations, but inconsiderable hills and monticles as well. For our classification is based essentially on geological structure and origin, and takes no note of the relative dimensions of hills and mountains. Amongst "accumulation mountains," therefore, we must arrange dunes, moraines, and all other hills which are due to the heaping-up of materials at the surface by natural causes. Many of these epigenetic hills are doubtless of insignificant size. Dunes and moraines, for example, do not very often exceed 100 feet, but now and again the former attain heights of 400 to 600 feet, while the latter not infrequently reach greater heights, sometimes forming hills over 1000 feet high.

(*b*) **Deformation Mountains.** — Under this head are included all mountains which owe their origin to deformation of the earth's crust. Three types are recognised, namely, *Folded Mountains* (due essentially to folding and crumpling of the crust), *Dislocation Mountains* (due to fracturing and dislocation of the crust), and *Laccolith Mountains* (due to bulging-up of the crust over intrusive masses of igneous rock).

1. *Folded Mountains.*—This type is much the most important, comprising, as it does, the greatest chains and ranges of the Old and New Worlds. The Alps, the Pyrenees, the Carpathians, the Himalayas, are all folded mountains, and the same may be said of the great mountain chains which extend almost continuously along the western borders of North and South America, and the corresponding chains and ranges of Eastern Asia and its archipelagoes.

All these mountains, however much they may differ in configuration, are characterised by a well-marked geological structure. They are composed essentially of highly flexed and folded strata. No doubt they show other structures—besides being folded, the rocks are often traversed by dislocations large and small, and by eruptive masses of different kinds. But it is the folded character of the strata which is the most essential and typical structure. Sometimes the folding is of a simple enough type. Occasionally, for example, the rocks entering into the formation of a mountain range are arched up in one single broad saddleback or anticline (see Fig. 138). Or in place of a great geanticline we may have a series of many symmetrical folds—the rocks rising and falling, as it were, in a succession of uniform undulations (see Fig. 139). But usually the structure is much more complex—the folds being no longer open and symmetrical, but closely compressed and inclined at all angles,

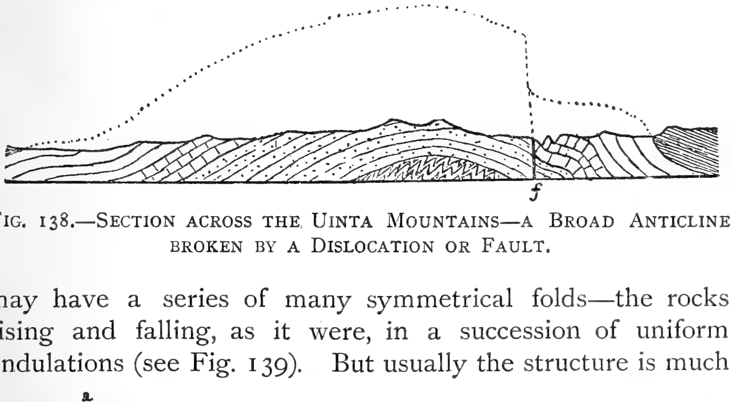


FIG. 138.—SECTION ACROSS THE UINTA MOUNTAINS—A BROAD ANTICLINE BROKEN BY A DISLOCATION OR FAULT.

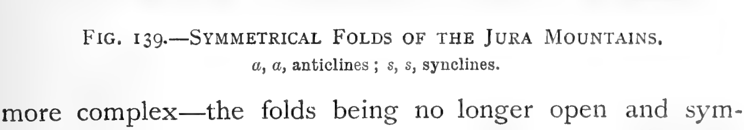


FIG. 139.—SYMMETRICAL FOLDS OF THE JURA MOUNTAINS.
a, a, anticlines; *s, s,* synclines.

or even, in many places, quite overturned and lying on their sides (see Fig. 140). This complex flexing and folding is usually, as already indicated, accompanied by great dislocations and displacements of the strata, and not infrequently by the appearance of veins, dykes, and irregular masses of formerly molten matter, which may traverse the disturbed strata in all directions.

When the present external form or configuration of folded mountains is compared with their internal or geological structure, the two are seldom found to coincide. The longitudinal ranges and intermediate longitudinal valleys of a mountain chain do not correspond save in a very general way with flexures or folds of the strata. Mountains do not necessarily or even often coincide with saddle-backed or arched structures—nor do valleys invariably or even frequently correspond with trough-shaped arrangements of the strata. Possibly, when a mountain chain came into existence, the external form of the region may have been more or less clearly an expression of the underground structure. That is to say, the mountain ranges may have coincided with anticlines, or saddle-backs, and the intervening hollows may have corresponded with geological synclines or troughs. But so long a time has elapsed since even the youngest of our mountain chains was upheaved, that the whole surface has been greatly modified. Everywhere we see evidence of enormous erosion and denudation. Vast masses of rock have been gradually worn down and removed—swept away as sediment from the heights, and distributed over the adjacent low grounds or upon the floor of the sea. Thus, in many places, the original configuration of a chain has been obliterated—saddle-backed mountains have been replaced

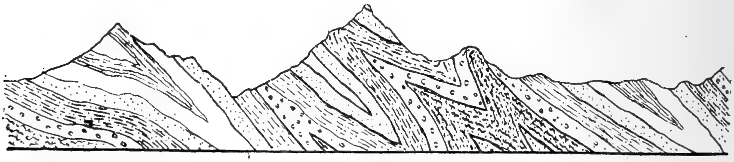


FIG. 140.—ALPINE TYPES OF UNSYMMETRICAL FOLDS.

by valleys and depressions, while trough-shaped strata have been carved into mountain heights (see Fig. 141).

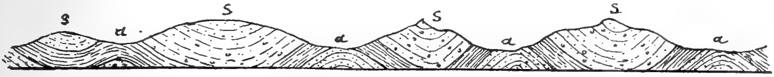


FIG. 141.—APPALACHIAN RIDGES OF PENNSYLVANIA.

a, *a*, anticlines; *s*, *s*, synclines.

The forms which folded mountains ultimately assume, under the action of denudation, are determined essentially by the character of the rocks and the mode of their arrangement. Certain kinds of rock and particular types of structure are more readily reduced than others. It is the more durable rocks and the stronger structures, therefore, that tend in the long-run to constitute the mountain ranges of a chain. In the younger mountain chains of the globe the remodelling of the surface is only partially accomplished. Consequently, amongst these the configuration is still in many places an expression of the underground structure. Individual ranges and intervening depressions continue to coincide more or less closely with the folds and displacements of the strata. But with increasing age such coincidence becomes less and less marked, until in the oldest mountain chains it ceases to appear. Amongst these ancient mountains, all weakly constructed heights, such as anticlinal ridges, have been reduced, while the more enduring rock arrangements, such as synclines or troughs, no longer form depressions, but have most frequently been converted into elevations by the removal of the weaker structures which formerly dominated them. The contrast is illustrated by Figures 139 and 141, the former representing the structure of a portion of the Swiss Jura—a relatively young chain, while the latter shows the Appalachian Ridges of Pennsylvania—mountains of vastly greater antiquity.

In both cases the strata, it will be observed, are arranged in symmetrical folds, but, as already stated, the structure of many mountain chains is much more complicated—the folds being closely compressed and pushed over, so as to lie on their sides. The configuration ultimately acquired by mountains of the Alpine type naturally differs from that assumed by an elevated region of symmetrically folded strata. Generally, we find that strata of variable character which have been compressed into a succession of steeply-inclined folds tend in time to assume the aspect of escarpment-mountains. The crests of the anticlinal ridges are removed, but the synclinal troughs are not developed into mountains, as in the case of symmetrically folded strata. It is the outcrops of the more durable rocks which determine the position of the heights—which, as a glance at Fig. 142 will show, are *escarpments*. The illustration, it need hardly be said, is only a diagram. In point of fact, the structure of such folded mountains is infinitely more complex, the folding being usually complicated by dislocations and displacements of all dimensions, and not infrequently by abundant intrusions of igneous rock. But in ancient mountains of this type the forms worked out by erosion and denudation are in every case determined by the character of the rocks and the mode of their arrangement. And as highly inclined folds are the rule in such mountains, the successive ranges carved out by epigene action frequently coincide with the outcrops of the more durable rocks—they are essentially escarpments—the escarpments and their dip-slopes becoming more and more pronounced as the axial planes of the folds are increasingly inclined from the vertical.

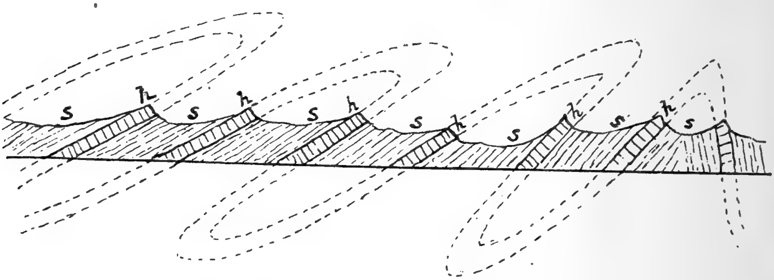


FIG. 142.—UNSYMMETRICAL FLEXURES GIVING RISE TO ESCARPMENT MOUNTAINS.

s, *s*, relatively "soft" rocks; *h*, *h*, relatively "hard" rocks.

If mountains are gradually lowered by denudation, it would seem to follow that they must in time be wholly reduced. Such, indeed, has been the fate of not a few mountain chains of great geological antiquity. Frequently we encounter plateaus and plains which, notwithstanding their superficial form, have all the structural characteristics of folded mountains. Thus, in former ages, an extensive range of mountains stretched across what are now the low-lying plains of Belgium. The structure of that region is highly complicated, the strata being arranged in a succession of closely compressed, unsymmetrical folds, so that younger rocks are folded underneath older rocks, while here and there the crust has yielded to the lateral movement by fracturing, and vast masses of strata have been thrust forward over the surface of rocks much younger than themselves. Yet the gently undulating ground gives no hint as to the presence of these buried mountain structures. The old mountains have been gradually removed and cast into the sea. Should the relative level of land and ocean remain unchanged for a sufficient space of time, a similar fate must overtake all mountains. But a multitude of facts conspire to assure us that this level has no permanency. We know that certain mountain chains, after experiencing enormous denudation, have been submerged or partially submerged, and become eventually buried in whole or in part under fresh accumulations of sediment, often of great thickness. Thereafter, crustal movements have again supervened; the old mountain-land has bulged up under the squeeze, and a new series of folds has been formed outside of and flanking the older series. With the re-elevation of the mountain area a new cycle of erosion is inaugurated, and in time the whole region may again be levelled, submerged, and eventually once more uplifted. Ranges which are the result of one earth-movement alone are termed *monogenetic;* those which, like the European Alps, owe their origin to two or more such movements are known as *polygenetic* chains.

The younger folded mountains of the globe are typically represented in the Old World by the great east and west ranges of the Alps, the Himalayas, etc., and in the New World by the vast Cordilleras of South America and the Rocky Mountains of North America. These chains usually consist of a series of more or less parallel ranges, which often interosculate or merge into one another. Sometimes they extend continuously in approximately straight or gently curved lines; in other cases, a chain may be more or less strongly bow-shaped. Followed in the direction of the general axis, the mountains usually become progressively higher until, towards the central portion, the greatest elevations are attained, after which the heights, as a rule, gradually diminish in importance. While many mountain chains form a compact system of ranges throughout their whole extent, others divide and break up, as it were, into a series of divergent ranges. In all cases the width of a chain of folded mountains is greatly exceeded by its length.

All these features, so characteristic of our younger chains, appear likewise to have distinguished the older folded mountains of the globe, many of which are now sorely wasted and reduced in height, while others have been wholly levelled.

2. *Dislocation Mountains.*—These are so termed because they owe their origin, not so much to folding as to fracturing and displacement of the crust. They usually occur in the form of more or less isolated heights or irregular shaped masses of elevated ground rising abruptly above adjacent lowlands. Mountains of this type are termed "Horste" by German geologists, who cite the Harz Mountains as a

prominent example. They are usually composed of very old rocks, and are severed by vertical dislocations from the low tracts that surround them. If the student will imagine a broad and lofty plateau to be cracked across in different directions by profound fractures, and the dislocated plateau to settle down irregularly, he will have some notion of the origin of Horste. Those segments of such a fractured plateau which have retained their original position are Horste, and they therefore testify to a former higher crustal level (see p. 179).

Occasionally, dislocation mountains occur as a series of parallel ranges, separated the one from the other by large vertical dislocations or normal faults. The ranges of the Great Basin, which extend north and south between the Sierra Nevada and the Wasatch Mountains, are of this type, and of similar origin are the Vosges and the Black Forest. The escarpments of these two mountain ranges face each other, separated the one from the other by long parallel lines of faults, between which the broad depression of the Rhine came into existence (see Fig. 143).

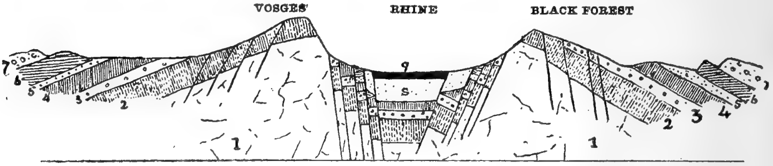


FIG. 143.—SECTION ACROSS THE VOSGES AND THE BLACK FOREST (PENCK).
1. Granite, etc.; 2-7, Mesozoic rocks; 8-9, Tertiary and later beds.

Dislocation mountains, like all other elevations, become modified by erosion and denudation, and are met with now in every stage of dissolution. Speaking generally, we may say that the best preserved examples are of relatively recent geological age. But some prominent Horste are of very great antiquity, their persistence being due to the simple fact that they consist of more durable rocks than the low-lying tracts above which they rise. In every case, however, it can be shown that such Horste have experienced excessive denudation.

3. *Laccolith Mountains.*—The leading characters of laccoliths have been discussed in Chapter XIII. Mountains of this

type are obviously due to the bulging-up of the crust over a concealed mass of molten matter (Fig. 66, p. 191). Laccolith mountains may formerly have been conspicuous in our own and other lands, where intrusive igneous rocks abound. Many boss-like masses and thick lenticular sheets of basalt and other rocks form conspicuous features in the Scottish lowlands (see pp. 191-195). These at the time of their intrusion were covered more or less deeply with sedimentary strata which they could not pierce, but may well have lifted up so as to cause prominent dome-shaped bulgings at the surface. But in the case of such ancient igneous rocks, so long a time has elapsed since their intrusion that any superficial bulging they may have caused has entirely disappeared. Recognisable laccolith mountains are necessarily of recent formation.

Erosion of Tectonic Mountains and Resulting Features.—Some tectonic mountains date back to a most remote geological antiquity, while others are young—not a few having come into existence in relatively recent times. In the case of the youngest mountains of this great class, internal structure, as might have been expected, not infrequently coincides more or less closely with external form or configuration. This correspondence is most clearly seen in recent Accumulation mountains, such as our still active volcanoes—the shape assumed by those mountains being obviously determined by the arrangement of their constituent materials. Nevertheless, even active volcanoes do not escape the modifying influence of the various epigene agents of change, but are attacked in the same way as mountains of every kind, old and young alike. In their case, however, the rate of decay is usually exceeded by the rate of growth. Hence the rugged furrows and gorges, gouged out by torrents on the flanks of a growing volcano, tend to be obliterated from time to time by the products of successive eruptions. But the great chains and ranges of Folded mountains cannot thus repair the ravages effected by epigene action. The growth of mountains of this type, we have every reason to believe, is a very gradual and protracted process. No sooner, therefore, does upswelling and wrinkling of the crust begin, than the slowly ascending surface is attacked by all the atmospheric agents of change. And so powerful and effective is this action, that if the rate of crustal movement did not exceed the rate of denudation, no mountain range could come into existence. It would be degraded as fast as it grew. Obviously, however, crustal deformation, no matter how gradual it may be, has in many, if not in all, cases exceeded the rate of denudation. Nevertheless, so potent are the agents of erosion that they have succeeded in very greatly modifying even the youngest elevations of the crust.

Although no portion of a growing mountain chain can escape this modifying influence, it is evident that the process of degradation must be carried on most actively along lines of water-flow. As torrents, streams, and rivers cut their way down into the massif, larger and larger surfaces of rock become exposed to subaërial action. The shattered débris, detached from cliff and mountain slope, slowly or more rapidly enters the drainage system, gradually becomes reduced in size, and is eventually swept away in the form of gravel, sand, and mud, beyond the limits of the mountain area. In time, therefore, profound and broad valleys are ploughed out, and these continue to be deepened and widened, as the process of mountain-making goes on. Thus, in the great transverse valleys which radiate from the backbone of a growing mountain chain, the rate of erosion keeps pace with or even exceeds the rate of rock-folding and uplift. New or secondary mountains gradually come into existence along the flanks of the primary elevations—a mountain chain, in a word, grows by the successive addition of contiguous parallel ranges. But the large transverse rivers flowing out from the primary axis are not deflected by the younger ranges which thus slowly rise across their path. The rate of valley erosion exceeds the rate of crustal deformation, and thus mountain range after mountain range is successively sawn across by the primeval rivers descending from the axis of the chain.

We may therefore conceive of the growth of a polygenetic mountain chain being continued through a long period of time—the gradually bulging and wrinkling crust being concurrently worn and furrowed by epigene action. The mountain-mass as a whole, however, continues to increase in elevation, notwithstanding the ravages of frost and glaciers, of rain and torrents, of streams and rivers. Only in the valleys does epigene action balance or exceed the elevating process. When at last all earth-movement ceases, the mountains are steadily reduced in height, while the valleys continue to be widened and deepened, until eventually the broad mountain-land may disappear and be replaced by a gently undulating plain—a *plane of erosion*.

Many such plains are known. That they occupy the site of vanished mountain chains is clearly indicated by their internal or geological structure. Some of these old plains of erosion, like that of the Belgian coal-fields, reach no great height above the level of the sea, while others attain considerable elevations, forming lofty plateaus. A study of such plateaus shows us that a chain of Original or Tectonic mountains, after it has experienced much denudation—after it has been reduced to its base-level and replaced by a plain of erosion—may again be uplifted. The crust may once more bulge up, and the *plain* be gradually carried to such a height that it then becomes a *plateau of erosion*. Or, instead of being thus elevated, the plain may become submerged for a longer or shorter period of time. During gradual and long-continued submergence, sediment may gather over the surface of the drowned land to such an extent that the site of the former mountain chain may eventually be buried under a thickness of many thousand feet of stratified materials —gravel, sand, mud, etc. Subsequently, the movement of depression ceases, and may be replaced by movement in the opposite direction—a general bulging-up or elevation of the area may take place. Should such ensue, then the buried plain of erosion will again rise out of the sea, and may even attain a height of many thousand feet above that level. In that case we should speak of the newly formed plateau as a *plateau of accumulation.* A section across it would show that the upper portion of the elevated area consisted of a great thickness of approximately horizontal strata resting upon and concealing the old plain of erosion.

Although Tectonic mountains tend to be gradually ground down to their base-level, it is seldom that the cycle of erosion is quite completed. Long before the mountains have entirely vanished, renewed crustal deformation may take place, and the much-denuded area be either re-elevated or submerged, according as the earth-movement is up or down. In the former case we get a plateau of erosion, the surface of which may be more or less irregular—ribbed and knotted with the straggling cores and stumps of the ancient mountains. In the latter case, the sorely-denuded mountain-land, carried down below sea-level, becomes in time covered with sediments, underneath which the lower lying parts of the plain of erosion may eventually become very deeply buried. Should the cores and stumps of the old mountains remain above sea-level as islets, they will, of course, escape burial, only to be subject, however, to continuous erosion. But should they be submerged, then they also will in time become partially or entirely concealed under gradually accumulating sediments. At a later period, should the sunken area be re-elevated to a very considerable height, we shall have a plateau of accumulation, consisting of approximately horizontal strata resting upon the irregular surface of the old plain of erosion. The horizontal strata will naturally attain their greatest thickness upon the lowest-lying portions of that plain, and will thin away as they approach the stumps of the degraded mountains—the summits of which may even peer above the surface of the plateau, as so many islets in a far-stretching sea.

2. SUBSEQUENT OR RELICT MOUNTAINS.—These have not been constructed or built as mountains, but are merely remaining portions or fragments of a formerly more extensive elevated area. They have been carved out of an old tableland and shaped into mountains by the gradual removal of masses by which they were at one time surrounded.

The form assumed by Relict mountains depends mainly upon the nature and arrangement of the materials out of which they have been carved. A plateau of accumulation, for example, tends to be cut up into a series of pyramidal or tabular mountains, and crested or flat-topped ridges, separating the various valleys from each other. And as the latter are deepened and widened, the massive segments of the old plateau become progressively narrower and gradually reduced in height. At a later stage most of these mountainous segments may have disappeared, and only a few isolated cones and ridges or truncated pyramids may be left. Finally, every height may be levelled, and the old plateau be replaced by a plain of erosion.

In the north-west of Scotland we have excellent examples of Relict mountains sculptured out of an ancient plateau of accumulation. In that region, certain old crystalline rocks (Archæan gneiss, etc.) had at a very early geological period been reduced to a base-level. The plain of erosion thus formed was then slowly submerged, and became in time covered with a great thickness of red sandstones. Long afterwards the whole region was re-elevated, thus forming a plateau of accumulation, the upper portion of which consisted of thick red sandstones resting on the surface of a plain of erosion composed of Archæan gneiss. So prolonged a period has elapsed since that epoch of elevation, that the red sandstones have been largely removed, and much of the old plain of erosion has been re-exposed. Very considerable masses of the overlying red sandstones, however, still remain, forming isolated cone-like or pyramidal Relict mountains, such as Canisp, Soulvein, Stackpolly, and Coulmore, or more closely associated aggregates of similar shaped heights, such as the Torridon Mountains.

Having glanced at the general character of Relict mountains which have been carved out of a plateau of accumulation —that is, out of an extensive elevated mass of horizontal or approximately horizontal strata—we may now shortly consider the character of the mountains which are chiselled out of a plateau of erosion. The relatively level surface of such a plateau is the result not of sedimentation but of denudation. A plateau of erosion may consist of many different kinds of rock, arranged in almost any way. In not a few cases, such plateaus represent the sites of vanished chains of Tectonic mountains. Externally they have a plain-like surface, internally they frequently show all the confused and complicated structures which are characteristic of true mountains of upheaval. Plateaus of this kind are well represented in Europe. The Highlands and Southern Uplands of Scotland, the Rhenish Schiefergebirge, the Scandinavian Mountains are all examples of highly denuded plateaus of erosion.

At a very early geological period, lofty ranges of Tectonic mountains extended over what are now our Northern Highlands and Southern Uplands. During prolonged ages those ancient Caledonian ranges were subject to erosion, until eventually they were largely reduced to their base-level—only a few sorely wasted stumps and cores projecting above a gently undulating plain of erosion. Subsequently depression ensued, and the plain of erosion became, over considerable areas, more or less deeply buried under sedimentary deposits. To trace the geological history in detail is here impossible—it is too long a tale to tell—and we need do no more than realise the fact that eventually all the depressed areas were again re-elevated *en masse*.

The Highlands and Southern Uplands then appeared as plateaus. Their configuration was upon the whole plain-like, the peripheral areas being to some extent occupied with approximately horizontal sedimentary strata, resting upon and concealing the old plain of erosion. In the central and more elevated portions of the plateaus that old plain formed the surface, and appears to have been here and there diversified by more or less abrupt heights—the worn and abraded torsos of the ancient Caledonian Mountains.

In the course of long ages the plateaus in question have experienced excessive denudation. To such a degree, indeed, have they been trenched and furrowed by multitudinous valleys, that they are now hardly recognisable as tablelands; their original plain-like character is well-nigh lost. They have been converted into rolling uplands, into regular ranges or irregular groups and masses of Relict mountains, the configuration and distribution of which have been determined very largely by the nature of the constituent rocks and the mode of their arrangement.

Sometimes, as throughout the larger portion of the Highlands and Southern Uplands, the Relict mountains have been sculptured out of the highly folded rocks forming the old plain of erosion; in other places, they are simply remaining portions of the younger rocks which overlie that plain; while in not a few cases, the upper part of a mountain consists of the younger, and its basal portion of the older, rocks, the line separating the two series representing the old plain of erosion.

The forms assumed by Tectonic (Folded) mountains, during the stage of early youth, are a more or less direct expression of their internal structure. The ranges coincide to some extent with upward folds or anticlines, and the intervening parallel hollows with downward folds or synclines (see Fig. 139, p. 397). But with increasing age this approximate correspondence between configuration and structure gradually disappears, until eventually every coincidence of the kind vanishes. Under the long-continued operation of the agents of erosion, the mountains are completely remodelled (see Fig. 141, p. 399). When a mountain chain has passed the age of maturity, the distribution and shapes of its component heights are determined directly by the character of the rocks and their geological structure. In this respect, therefore, highly denuded Tectonic mountains do not differ from Relict mountains which have been carved out of an ancient plateau of erosion. In both cases it is the character or nature of the rocks and the mode of their arrangement which determine the position of the heights and their general configuration. Nevertheless, we must distinguish between the two kinds of mountains. A Tectonic mountain chain remains *original* throughout all stages of its existence ; it is a true Deformation mountain chain until it is at last swept away, and replaced by a plain of erosion. A Relict mountain has not been built up, nor is it the direct result of crustal deformation. It owes its existence to erosion ;—it is a mountain of circumdenudation. But the very causes which have determined its existence must eventually work out its destruction.

We have referred to the forms assumed by mountains which have been carved out of plateaus of accumulation—pyramids, and truncated pyramids being the typical shapes of such mountains. Under favourable conditions mountains of this kind often ascend in a series of abrupt terraces, or corbel steps. But much depends on the nature of the rocks. If the strata be more or less homogeneous in character, the step-like outlines are not likely to be pronounced. Instead of abrupt pyramidal heights, we may have smooth, rounded hills. The character of the climate has also a powerful influence—an arid climate fostering the formation of more or less abrupt pyramidal mountains ; while under moist conditions the configuration of the heights tends to be smoother and less abrupt. Nevertheless, whether the horizontally bedded rocks be of one kind or another, or show alternations of many different kinds, and whether the climate be dry or humid, equable or the reverse—tropical, temperate, or arctic—the mountains and hills sculptured by the action of the epigene agents are of the same type.

Relict mountains derived from the erosion of folded and contorted rocks have, as already shown, the general aspect of highly denuded Tectonic mountains. Hence sometimes we find them extending in the direction of the outcrops of the more durable rock-masses, and then forming more or less regular ranges. In other places, again, owing to the presence of confused and complicated structures, the heights may exhibit little or no trace of alinement, although it is obvious that in this case, as in the other, the position of the mountains has been determined by the nature of the rocks and their arrangement.

Plains and plateaus do not necessarily consist either of horizontal or of highly contorted rocks. Between these two extremes of rock-structure there are many gradations. The degree of crustal deformation varies indefinitely. There are wide regions throughout which the rocks show only long, gentle undulations—the inclination of the strata from the horizontal not exceeding a few degrees. The Midlands of England, for example, are composed of rocks which have a general dip at a low angle towards the east. Throughout the Central Lowlands of Scotland, from the base of the Grampians to the foot of the Southern Uplands, steep dips are exceptional. And the same may be said of many other parts of the world. Away from regions of mountain-uplift, indeed, there are vast continental tracts throughout which the strata show little disturbance—the beds rising and falling in more or less gentle undulations. Sometimes the undulations succeed each other somewhat rapidly; in other places the crust has been bent up in one broad, depressed arch, measuring many miles across. In highly denuded countries the tops of the anticlinal arches—the crests of the undulations—have invariably been removed, and the truncated ends of the beds exposed. In other words the shape or form of the ground does not coincide with the undulations of the strata, but is the result of erosion.

The most characteristic type of hill or mountain carved out of rocks which have a gentle dip or inclination is the *Escarpment*, the conditions for the formation of which are referred to in Chapter XIX. This is the type of hill most commonly met with in Central England. A glance at any geological map of the country will show that all the prominent hills and high grounds are developed along the outcrops of the Jurassic limestones and the Chalk, and thus have a general northerly or north-easterly trend. Proceeding from the foot of the Malvern Hills towards the east, we first traverse low-lying plains of sandstone and argillaceous strata, until on the other side of the Severn we reach the Cotswolds, composed principally of limestones, which, as they dip gently eastwards, are succeeded by a series of argillaceous beds, forming again a region of undulating plains. Continuing our traverse in the direction of the dip, we eventually encounter another broad belt of high ground—the escarpment of the Chalk. This escarpment is succeeded in its turn by a low-lying region composed mostly of soft clay strata, and other more or less non-indurated materials.

When the strata, instead of being inclined in one direction for long distances, are arranged in a series of gentle folds, escarpments continue to present themselves wherever relatively hard beds crop out at the surface. In this way we not infrequently find lines of escarpment facing each other, as in the well-known case of the North and South Downs which overlook the intervening Weald. Here we have an example of a highly eroded anticlinal fold, which is always a weak structure, and readily reduced by epigene action. (Fig. 144.)

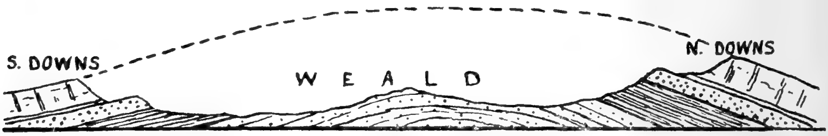


FIG. 144.—SECTION ACROSS THE WEALDEN AREA—A DENUDED ANTICLINE.

Synclinally arranged strata do not succumb so easily—the structure is relatively strong, and makes a stouter resistance. The rocks so arranged are not degraded so rapidly as the same rocks would be if disposed in the form of an anticline. In short, it is with gently undulating strata as with the steeper and more abrupt convolutions of Tectonic mountains —anticlines are frequently replaced by hollows, while synclines tend to be developed into heights.

In fine, one may say that however simple or complex the geological structure of a highly denuded region may be, the configuration of the ground, as worked out by epigene action, has been determined mainly by the character of the rocks and the manner of their arrangement. In a word, when we have deciphered the geological structure of a country, we have at the same time discovered the origin of its hills and mountains.

2. PLAINS AND PLATEAUS

In discussing the structure and origin of mountains, some reference has been made to the formation of plains and plateaus. It may be well, however, to summarise here the general characters of those particular land-forms.

(*a*) **Plains.**—These may be defined as areas of approximately flat or gently undulating land. They are usually confined to lowlands, but in the case of very extensive areas the surface of a plain may rise by almost imperceptible degrees to a height of several thousand feet. This, however, is exceptional, such elevated tracts being usually termed plateaus.

Plains of Accumulation.—These are built up of horizontal strata, so that the surface is a more or less exact expression of the internal geological structure. Plains of this type have been formed in various ways. Many are of lacustrine, fluviatile, or estuarine origin; in other words, they consist of undisturbed aqueous deposits. Others, again, such as many coastal plains, have been formed partly by aqueous sedimentation, and partly by wind blowing sand before it from exposed beaches. When a plain occurs at or near a base-level of erosion, rain and running water have little effect upon it—the process of denudation is practically at a standstill. Under certain conditions, however, the surface may be considerably modified by the action of wind. For example, deltas and coastal plains margined by the sea or by an extensive lake, are not infrequently invaded by sand dunes. The higher a plain rises above its base-level, the more does it become subject to denudation—high-lying plains usually showing a more irregular and undulating surface than those occurring at lower levels. It must be noted, however, that the form of the surface depends to a large extent upon the nature of the materials of which the plain is composed. Other things being equal, a plain consisting chiefly of impervious deposits is more readily eroded than one built up largely of gravel and sand and other more or less porous accumulations. As examples of plains of accumulation may be mentioned the fluviatile plains and deltas of the Nile, the Danube, the Ganges, the Amazon, the Mississippi, and other rivers, the grassy Steppes of Russia, the Aralo-Caspian depression, the Tundras of Siberia, the Llanos and Pampas of South America, etc.

Plains of Erosion.—Plains of this class are distinguished by the fact that the surface does not necessarily coincide with the underground structure—in the great majority of cases, indeed, there is no such correspondence. It is only when a plain has resulted from the reduction of a series of horizontal strata that external form and internal structure can agree. Plains of erosion may be said to represent the final stage of a cycle of erosion—they are the base-levels to which old land-surfaces have been reduced. Occurring, as they usually do, at low levels, they are liable to become covered with alluvial and other deposits, and thus at the surface to show as plains of accumulation. Occasionally, plains of erosion have been submerged and covered more or less deeply with marine deposits. Consequently, when re-elevation supervened, the regenerated lands presented the appearance of plains of accumulation. It seems not unlikely, indeed, that the majority of the latter are merely superimposed on pre-existing plains of erosion. The broad, low-lying tracts through which the larger rivers of the globe reach the sea are probably in many cases plains of erosion more or less covered and concealed under alluvial deposits.

Plateaus or Tablelands.—The term plateau is usually applied to any flat land of considerable elevation which is separated from contiguous lowlands by somewhat steep slopes. It is not always possible, however, to draw a distinction between plains and plateaus—for, after all, a plateau is only an elevated plain. Standing at a higher level than plains, plateaus are necessarily subject to more active and intense erosion, and, according to their age, are correspondingly incised and denuded. Plateaus of all kinds, as we have learned, tend to acquire a mountainous character—to be converted, in short, into groups or ranges of relict mountains.

Plateaus of Accumulation.—These are distinguished by the fact that they are built up of horizontal or approximately horizontal strata; their general or average surface, therefore, corresponds with the geological structure. As examples of plateaus of this type may be cited the Plateau of the

Colorado, the Uplands of Abyssinia, and the Deccan of India —all more or less highly denuded regions.

Plateaus of Erosion.—The general surface of these plateaus having been determined by denudation, it rarely or never coincides with the geological structure. But the structure and origin of erosion plateaus have already been sufficiently discussed.

3. VALLEYS

By the term *valley*, we usually mean the hollow or depression through which a stream or river flows. Some valleys, however, contain no streams, but are mere elongated depressions. With relatively few exceptions, valleys are either (*a*) the direct result of erosion or (*b*) have been greatly modified by it. If we consider the latter, however, from the point of view of their origin, they must be distinguished from true erosion valleys—just as tectonic mountains must be recognised as such, even although they have all been more or less modified by denudation. We can therefore group valleys in two classes:—(1) Valleys which owe their origin either to hypogene action or to epigene action other than that of erosion; and (2) valleys which are true hollows of erosion.

1. ORIGINAL OR TECTONIC VALLEYS.—These are of two kinds—(*a*) elongated hollows produced by the irregular accumulation or heaping-up of materials at the surface; and (*b*) depressions which are the result of crustal deformation.

(*a*) **Constructional Valleys.**—This class of valley is of little importance. It is represented in volcanic regions by depressions occurring in the surface of various volcanic accumulations, and by the now and again pronounced hollows that separate adjacent cones, lava-flows, or heaps of ejecta. Similarly, the depressions lying between ranges of dunes and moraines may be termed constructional valleys. In a word, any hollow at the surface caused by the irregular distribution of materials, whether by volcanic action or by epigene action of any kind, would come under this head.

(*b*) **Deformation Valleys.**—Theoretically, we may group these as (1) *Dislocation Valleys*, and (2) *Synclinal Valleys*. Not infrequently, however, a deformation valley has been determined partly by fracture and partly by flexure, such as the valley of the Jordan. Dislocation valleys may extend for long distances between parallel faults, or they may follow the line of one great dislocation alone. Such valleys are approximately straight or gently sinuous, and are of not infrequent occurrence. Glen App in Ayrshire and the great hollow traversed by the Caledonian Canal are examples in this country. Another good example is the valley of the Rhine between the Vosges and the Black Forest. Synclinal valleys are best developed in regions of recently uplifted tectonic mountains, the surface features of which not infrequently coincide more or less closely with the underground rock-structure. Such valleys naturally trend in the same general direction as the mountains amongst which they occur.

Tectonic valleys are, of course, liable to modification by erosion. Dry valleys, whatsoever their origin may have been, may remain for long periods comparatively unchanged. It is true that in desert regions such valleys are subject to the action of the wind, which widens and sometimes deepens them, but wind-eroded valleys are exceptional. Wherever rain falls and water flows, however, we look for evidence of erosion. Under ordinary conditions even the most recently formed dislocation and synclinal valleys have become modified. And in regions exposed for a prolonged period of time to denudation, such valleys as coincide with dislocations are obviously wholly the work of erosion. They have been worked out along lines of weakness, which affect a great thickness of rocks. However much, therefore, a land-surface may be lowered by denudation, the same faults will continue to guide the agents of erosion. The land may have been planed down again and again to base-level—it may have experienced more than one cycle of erosion—but with each re-elevation, valleys of erosion tend to reappear along the same lines of weakness. Synclinal valleys, on the other hand, are much less persistent. When we find a river following a synclinal hollow, we may usually feel assured that the hollow is of relatively recent geological age. For the synclinal structure is more durable—less readily reduced than the anticlinal folds on either side. The latter are prone to collapse, and thus in time the lines of drainage become modified. A river which at first followed a synclinal trough tends gradually to shift its course as the contiguous anticlines are reduced, and ere long the syncline is abandoned in whole or in part. Even amongst folded mountains of relatively recent age, the longitudinal or strike-valleys often do not coincide with synclinal troughs—they have forsaken these, and now flow in true valleys of erosion.

2. SUBSEQUENT OR EROSION VALLEYS.—No hard-and-fast line can be drawn between Tectonic valleys and Erosion valleys, for many valleys are partly of original, partly of subsequent origin, as is well seen in regions of recent mountain-uplift. In the vast majority of cases, however, the valleys through which rivers run are hollows of erosion. The main lines of drainage have doubtless been determined by the original inclination of the surface—but the actual formation of the valleys themselves is the result of epigene action alone. Let us picture to ourselves some extensive land-area just newly raised above the level of the sea. We shall suppose that the surface is very gently undulating, and that it rises gradually from the sea-coast, and culminates in a more or less abrupt tract of high ground which represents, let us say, the cores or stumps of some ancient reduced mountain chain—mere torso-mountains overlooking a broad tableland that sinks gradually seawards. It is obvious that the new-born rivers would necessarily follow the slope of the ground; their direction would be determined by the configuration of the surface. At first these primeval rivers might have few, if any, tributaries. As time went on, however, many lateral brooks and streams would come into existence. The land, we shall suppose, consists of many different kinds of rocks arranged in many different ways. Consequently these would yield very unequally—gradually relict hills would come into existence, owing to the reduction of the less resistant rocks and rock-structures in their vicinity. In a word, the undulating land would tend in time to show a more diversified surface—heights and hollows would become more pronounced. Meanwhile, the main rivers have been continually widening and deepening their courses. Where they traverse relatively hard rocks, the valleys are narrow,

forming, it may be, ravines and gorges; where only soft rocks and yielding structures have been encountered, the valleys are relatively wide. In short, the rate of erosion will vary in the valleys, just as it does over the surface of the land generally. Thus it will come to pass that the ravines and gorges of the rivers will mark the outcrops of those hard rocks which, outside of the valleys, form hills, ridges, or escarpments, while the more open reaches of the valleys will coincide with the outcrops of the relatively soft rocks, which throughout the region have determined the position of the lower grounds. The gradual development of surface features implies, of course, the growth of a secondary drainage system. Here and there the trunk rivers are joined by tributaries, formed by surface-waters making their way down the slopes of the land and converging in those depressions that open directly upon the wider reaches of the river-valleys. As the main rivers continue to deepen and widen their valleys, their tributaries will be correspondingly active, and still younger brooks will begin to appear further inland, as the lateral streams cut their way back into the heart of the country. Eventually, when the whole drainage system has reached maturity, the catchment area of each large river will show a more or less complex network of tributaries large and small. The whole surface of the tableland will now be broken up to such an extent that it may be hard to realise its primeval configuration. Nevertheless, the general inclination of the original surface will be indicated by the trend of the chief rivers. That trend being quite independent of the geological structure, the rivers have cut their courses across soft and hard rocks alike—they seem to ignore all obstacles, traversing hill-ranges and escarpments just as if they had followed lines of gaping faults or fissures. All these apparent obstacles had no existence, however, when the rivers began to flow. They have been slowly developed during the gradual denudation or lowering of the surface, and while the intersecting valleys were at the same time being deepened and widened. In a word, the formation of river-gorges, hill-ranges, and escarpments has proceeded contemporaneously. The direction of the main lines of drainage has thus been determined by the original slope of the land, while the subsequent erosion of that surface slope, guided and influenced by the varying character and structure of the rocks, has determined the lines followed by tributary streams and brooks.

A typical river shows an upper or torrent-track, a middle or valley-track, and a lower or plain-track. In the torrent-track, erosion is at a maximum and deposition of sediment at a minimum; in the valley-track, erosion does not proceed so rapidly, while here and there considerable deposition may take place; in the plain-track, erosion practically ceases and deposition is at a maximum. The plain-track may therefore be looked upon as the base-level to which every river strives to reduce its bed. As erosion proceeds, the plain-track gradually extends inland so as to gain upon the valley-track. The latter in like manner is continually encroaching upon the torrent-track, while the torrent-track in its turn constantly eats into the high ground where it takes its rise. In the earlier stages of valley-formation, it is obvious that the original configuration of the surface and the varying character of the rocks and rock-structures may cause the appearance of many cascades, waterfalls, and rapids in all parts of a young river's course. But such obstructions tend gradually to disappear as erosion proceeds, hard rocks and resistant rock-structures are eventually reduced, and an equally graded channel finally results. The stage of maturity has now been reached—the valley showing a true curve of erosion—being relatively steep in its upper course, but rapidly flattening out as it descends to the base-level. Hence in all regions which have been exposed to the action of subaërial erosion for a prolonged period of time, considerable waterfalls ought not to occur. If they should appear in a long-established hydrographic system, we may suspect that the drainage-system after having attained maturity has subsequently been interfered with. Waterfalls cannot be of any great age. Sooner or later they must be cut back and replaced by ravines or gorges. Their presence, therefore, shows either that the valleys in which they occur are throughout of recent age, and that the rivers have not yet had time to reduce such irregularities, or that the drainage-system, if long-established, has since been disturbed by some other agent than running water. In deformation-mountains of recent age, we naturally expect to meet with cascades and waterfalls, for the streams and rivers of such a region are relatively young. They have only, as it were, commenced the work of erosion. But plains and plateaus of erosion which have existed for ages as dry land, and in which a complete hydrographic system has long been established, should show no great waterfalls. Yet we find cascades and waterfalls more or less abundantly developed in all the plains and plateaus of Northern Europe, and the corresponding latitudes of North America; and most of these lands are of very great antiquity, their main lines of drainage having been established for a long time. Obviously, the hydrographic systems have been disturbed, and the disturbing element has been glacial action. During the Ice Age the long-established pre-glacial contours were greatly modified. Frequently, indeed, the minor valleys in plateaus and plains were obliterated, while even the main valleys were often choked with débris. When glacial conditions passed away, and streams and rivers again flowed over the land, they could not always follow the old lines of drainage continuously, but were again and again compelled to leave those, and to cut out new courses in whole or in part. Hence the frequent occurrence of cascades and waterfalls in formerly glaciated lands.

Another cause for the existence of waterfalls in long-established drainage-systems must be sought for in crustal disturbances. In general, deformations of the crust would seem to have been very gradually brought about, so gradually, indeed, that they have often had little or no influence upon the courses of great rivers. Anticlines slowly developing across a river-valley have been sawn through by the river as fast as they arose. Dislocations, in like manner, would seem to have been very slowly developed. Frequently these have traversed a river-valley without in any way disturbing the drainage, the rate of erosion having been equal to that of displacement. On the other hand, we know that faulting or dislocation may sometimes be effected suddenly. Were a fault to be developed across a river-valley either suddenly or at a greater rate than the rate of erosion, and were its downthrow to be in the direction to which the river flowed, a waterfall would certainly be the result.

4. BASINS

We have now considered the origin of the more important surface features—mountains, plains, plateaus, and valleys—and briefly indicated to what extent the varying character of rocks and rock-structures has influenced their development. There is yet another interesting class of land-forms deserving of attention by the student of structural geology. We refer to the larger and smaller depressions of the surface, the majority of which are now or have formerly been occupied by water. Like other superficial features, *Basins* are of various origin, some being the result of crustal deformation, others owing their formation to epigene action, while yet others are due to both.

(*a*) **Tectonic Basins.**—Most of the larger lakes and many inland seas occupy basins which have come into existence during earth-movements. In some cases these depressions are geosynclines—the result of a local sagging or subsidence of the crust, not necessarily accompanied by fracture and dislocation. In other cases, subsidence has taken place along lines of faulting and disturbance. Some basins, again, would seem to have come into existence between contiguous high grounds undergoing elevation. The great lake-basins of Russia and North America (Onega, Ladoga, Superior, Huron, Michigan, etc.), and the extensive Aralo-Caspian depression, with its numerous sheets of water and desiccated basins, are essentially geosynclinal troughs. The Dead Sea and the lakes of Equatorial Africa, on the other hand, occupy depressions caused by fracture and displacement. It is worthy of note that Tectonic basins are not confined to any particular latitude. A considerable number, apparently the majority, occur in relatively dry and rainless regions—both at low and high levels. On the other hand, not a few are met with in temperate and well-watered lands, of which the large Russian and North American lakes are the most notable examples.

(*b*) **Volcanic Basins.**—The most typical basins of this class mark the sites of extinct volcanoes. Many lakes, for example, occupy the cup-shaped depressions of volcanic cones; or the deep concavities in the surface of the land (explosion craters) produced by paroxysmal outbursts. The Maars of the Eifel, and the numerous crater-lakes of Auvergne and Central Italy, are well-known types. Other volcanic lakes occupy what may be termed barrier basins, and owe their origin to the obstruction of the drainage by lava or fragmental ejecta. The Lac d'Aydat of Auvergne, for example, is confined by a barrier of lava.

(*c*) **Dissolution Basins.**—These may be shortly defined as depressions of the surface caused by the gradual removal of underlying soluble rock. They are the result, in short, of the chemical and mechanical action of underground water. Such depressions are of common occurrence in regions where massive limestones occupy the surface, and are caused by the falling-in of subterranean galleries, tunnels, caves, etc. Owing to the highly fissured character of the limestone, these depressions seldom contain lakes. Now and again, however, after very heavy rain which the underground channels are unable to dispose of at once, temporary lakes come into existence. Even permanent lakes are occasionally present in such regions. These may sometimes be the result of crustal movements which have brought the fissured bed-rock under the influence of the subterranean water-level. In most cases, however, such lakes probably owe their origin to the closing of the underground outlets by the accumulation of red earth and débris. Occasionally, in glaciated limestone regions, the depressions have been rendered water-tight by the deposition of morainic materials. Dissolution basins not infrequently occur in places where the bed-rocks, although themselves of a more or less impermeable character, are yet underlaid at a greater or less depth by soluble material such as rock-salt or gypsum. The gradual removal of these by underground water eventually brings about slow subsidence or sudden collapse of the surface.

(*d*) **Alluvial Basins.**—Owing to irregular accumulation of sediment, shallow depressions are of common occurrence in deltas and other broad fluviatile and estuarine flats. These during floods may become lakes, temporary or permanent, as the case may be. The deserted "loops" of rivers, and the pools and "creeks" which occupy the deeper hollows of dried-up river-courses, come under the same head. Again, lakes may be formed in valleys by the disproportionate accumulation of sediment by a river and its tributaries. The river, by carrying down large quantities of material, may gradually raise the surface of its bed above that of its affluents, in the lower reaches of which barrier-lakes will thus be formed. Or the tributary streams may throw more detritus into the main valley than the river occupying the latter can carry away. Barriers are thus produced, and large valley-lakes appear above the obstructions, of which some of the lakes in Upper Engadine (Silser See, Silvaplana See) are examples.

(*e*) **Æolian Basins.**—These are more interesting than important, and are naturally confined to relatively dry regions. Some owe their origin to the erosive action of wind, while others are constructional—that is to say, they are hollows lying amongst wind-blown accumulations.

(*f*) **Rock-fall Basins.**—These are caused by landslips, etc., obstructing the drainage, and are usually of little importance. As we should expect, they are of frequent occurrence in regions of recent mountain-uplift, where the geological structures are weak and liable to collapse.

(*g*) **Glacial Basins.**—The basins included under this head are of various origin—some being true hollows of erosion, others constructional, *i.e.* due to the unequal heaping-up of detritus, while many are partly one and partly the other. Hence, some lakes of glacial origin occupy true rock-basins, and others are essentially barrier-basins. All the large tectonic basins, in so far as they are due to crustal deformation, might be described as rock-basins, while certain volcanic basins would likewise come under the same category. But in these cases the depressions are obviously related to geological structures—geosynclines, dislocations, crateral hollows. Rock-basins of glacial origin differ from all others in the fact that they are totally independent of geological structure and the character of the rocks themselves. They are met with alike in igneous, metamorphic, and derivative rocks —whether these be relatively "hard" or "soft"—and they occur indifferently in regions of horizontal, gently inclined, highly flexured, and contorted strata. As might have been expected, both rock-basins and barrier-basins of glacial origin are confined to regions which are proved by other evidence to have been formerly occupied by snow-fields and glaciers. And those glaciated regions are pre-eminently the lake-lands of the world. In Europe, for example, very few lakes occur outside of the glaciated areas over which ice-sheets and glaciers formerly extended—the more notable exceptions being the volcanic basins of Auvergne, the Eifel, and Central Italy. In North America the same remarkable distribution of lakes may be seen. Throughout the extensive regions lying north of the glacial boundary, they are exceedingly numerous, while south of that line they are almost unknown. Of the few lakes which occur in regions which have never been subjected to glaciation, the more important occupy tectonic and volcanic basins.

Unless they be very capacious and extensive, basins soon become obliterated. Erosion and sedimentation are too active to permit of their prolonged duration. Exceptionally, basins which occur in dry and practically rainless tracts where erosion and deposition are at a minimum, may persist for lengthened periods of time. The saline and alkaline lakes of such regions are in many cases visibly drying up, and wind-blown sand is encroaching upon their desiccated floors. Again, tectonic basins may long outlive the land-surface upon which they first appeared. Should the floor of such a basin, occupied by a great lake, continue to subside at approximately the same rate as it is being filled up with sediment, and the effluent river cannot in the meantime succeed in draining the water away, it is obvious that the lake may persist for a very long time. A vast thickness of sediment might come to accumulate upon its floor, although the depth of the lake might never have exceeded a few hundred feet. The lake would in such a case form the base-level for all the surrounding region, the surface of which, perhaps mountainous to begin with, would be gradually lowered, and might pass through a complete cycle of erosion before the lake ceased to exist. In a word, a great lake or inland sea may become the burial-place of the high grounds that drain towards it, for it bears the same relation to these as an ocean to a continent. Relatively few lakes, however, occupy tectonic basins. Of these the majority, as we have seen, occur in dry regions, where river-action is at a minimum, and where consequently the depressions caused by crustal deformation persist either as dry or only partially filled basins. The rate of subsidence has exceeded the rate of sedimentation, and as the lakes seldom or never overflow, save only in very wet years, their rims are not cut down by river-erosion. The large lakes of Northern Europe and North America are also tectonic basins, largely modified, however, by glacial erosion and accumulation. They probably came into existence underneath the great ice-sheets which formerly covered those regions, and at a time, therefore, when ordinary fluviatile action was largely in abeyance. They could neither be silted up by sedimentation, nor breached by the action of outflowing water, and too short a time has elapsed since the glacial period to allow of their obliteration by these causes. In well-watered regions all depressions of the surface, whatsoever their origin may be, must sooner or later disappear—the beautiful lakes of our temperate lands and mountain areas are merely evanescent features.

5. Coast-lines

The coast-lines of the globe are the joint-product of hypogene and epigene action. Their general trend is mainly due to crustal movement, and is naturally determined by the position of the continents in relation to the great oceanic depression. The former are nowhere co-extensive with the true continental plateau, considerable areas of which in many parts of the world are below the sea-level. When the continental coast-lines approach the margin of that plateau, they usually continue for long distances in one direction, are rarely much indented, and show few or no fringing islands. Conversely, when they recede from the edge of the continental plateau, their trend becomes irregular, numerous inlets appear, and marginal islands often abound. A highly indented coast-line like that of North-west Europe, of Greece, and other parts of the Mediterranean lands, of Alaska, and many other regions, is the result of subsidence—the inlets and fiords are merely the submerged lower reaches of old mountain valleys, the marginal islets are the higher portions of otherwise sunken tracts.

On the other hand, the forms assumed by coasts is the result of epigene action, guided and controlled, so to speak, by the character of the rocks and their geological structure.

APPENDICES

APPENDIX A

TABLE OF BRITISH FOSSILIFEROUS STRATA

QUATERNARY or POST-TERTIARY.	**Recent and Post-glacial (Neolithic, etc.)**		Raised Beaches and Estuarine Flats; Lacustrine and Fluviatile Deposits; Bogs or Peat-Mosses; Moraines and Fluvio-glacial Gravels, etc.
	Pleistocene or Glacial (Palæolithic)		Late Glacial Deposits; Interglacial Deposits; Glacial and Fluvio-glacial Deposits.
CAINOZOIC or TERTIARY.	**Pliocene**	Newer	Cromer Forest-bed Group. Weybourn and Chillesford Crags. Norwich Crag. Red Crag.
		Older	St Erth Beds; Coralline Crag; Lenham Beds, etc.
	Miocene		(Wanting in Britain.)
	Oligocene		Hamstead Beds. Bembridge Beds. Osborne or St Helen's Beds. Headon Beds. Bovey Tracey Beds and Leaf Beds of Mull, Skye, and Antrim.
	Eocene	Upper	Headon Hill Sands; Barton Clay; Upper Bagshot Sands.
		Middle	Bracklesham Beds and Middle Bagshot Sands.
		Lower	Lower Bagshot Sands. London Clay and Bognor Beds. Oldhaven Beds. Woolwich and Reading Series. Thanet Sands.
MESOZOIC or SECONDARY.	**Cretaceous**	Upper	Upper Chalk. Middle Chalk. Lower Chalk and Chalk Marl. Upper Greensand. Gault.
		Lower	Lower Greensand. Weald Clay. Hastings Sand.

MESOZOIC or SECONDARY.	**Jurassic**	UPPER or PORTLAND OOLITES	Purbeck Beds. Portland Beds. Kimeridge Clay.	
		MIDDLE or OXFORD OOLITES	Coral Rag. Oxford Clay.	
		LOWER or BATH OOLITES	Cornbrash and Forest Marble. Great or Bath Oolite, with Stonesfield Slate. Fuller's Earth. Inferior Oolite.	
		LIAS	Upper Lias. Marlstone. Lower Lias.	
	Triassic	RHÆTIC	Penarth Beds.	
		UPPER or KEUPER	New Red Marl. Lower Keuper Sandstone.	
		MIDDLE	(Wanting in Britain.)	
		LOWER or BUNTER	Upper Mottled Sandstone. Pebble Beds. Lower Mottled Sandstone.	
PALÆOZOIC or PRIMARY.	**Permian**	UPPER	Red Sandstones, Clays, etc. Magnesian Limestone. Marl Slate.	
		LOWER	Red Sandstones, Clays, Breccias, and Conglomerates.	
	Carboniferous	COAL-MEASURES	Red Sandstones, and Upper Coal-bearing Series. Middle Coal-bearing Series. Lower Coal-bearing Series ("Ganister Beds").	
		MILLSTONE GRIT	Thick Sandstones, etc.	
		CARBONIFEROUS LIMESTONE	Yoredale Beds. Main or Scaur Limestone. Lower Limestone Shale (England), and Calciferous Sandstones (Scotland).	
	Devonian and Old Red Sandstone		Upper Devonian Middle „ Lower „	Upper and Lower Old Red Sandstone.
	Silurian	UPPER	Ludlow Group. Wenlock Group. Llandovery Group.	
		LOWER (*Ordovician*)	Bala and Caradoc Group. Llandeilo Group. Arenig Group.	
	Cambrian	UPPER	Tremadoc Slates. Lingula Flags.	
		MIDDLE	Menevian Group.	
		LOWER	Harlech and Llanberis Group.	
Archæan and Pre-Cambrian			Torridon Sandstones, etc. Lewisian or Hebridean Gneiss.	

APPENDIX B

THE SCALE OF HARDNESS

1. Talc.
2. Rock-salt or Gypsum.
3. Calcite.
4. Fluor-spar.
5. Apatite.
6. Orthoclase.
7. Quartz.
8. Topaz.
9. Corundum.
10. Diamond.

APPENDIX C

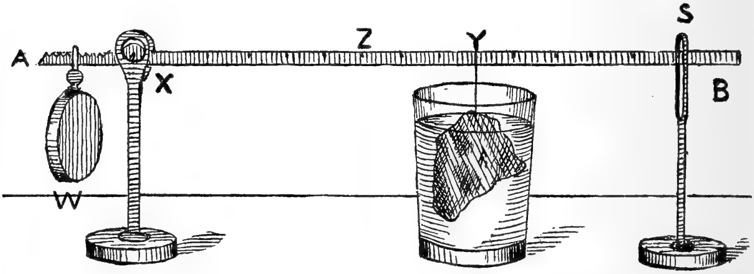
TRUE AND APPARENT DIP

In the late Professor A. H. Green's admirable *Physical Geology* the student will find a full statement of the methods employed for ascertaining the amount and direction of the true dip from measurements of the apparent dip exposed in two sections making a large angle with one another. The student may usefully consult also Mr Penning's *Field Geology*, and the same author's *Engineering Geology*, on the same subject. A little experience, however, will soon convince the observer that the accuracy of an isolated dip obtained in this way can only be relied upon for the particular spot at which it is taken. Unless it be confirmed by more or less numerous observations in the neighbourhood, the precise direction and amount of the dip calculated from two or more apparent dips may not have much significance. We judge so from the fact that in regions where outcrops are abundantly exposed, the direction and angle of dip often vary within short distances. Not much reliance, therefore, can be placed upon an isolated dip, no matter how carefully its direction and angle have been calculated. The probabilities, however, are that the field geologist will seldom or never have occasion to use any of the methods or formulæ referred to.

APPENDIX D

THE SPECIFIC GRAVITY OF ROCKS

Walker's Specific Gravity Balance is largely used by geologists, the results obtained from it being sufficiently accurate for all practical purposes. The principle of this little machine will be readily seen from the accompanying illustration.



"A B is a lever resting on knife-edges at X, and graduated from X to B in inches and tenths (hundredths must be guessed). W is a weight which can be moved out or in on A B to suit the size of the specimen weighed. S is an upright with a vertical slot to receive and steady the lever.

The piece of rock or mineral to be tested is suspended from the lever A B by a fine thread, and weighed in air. The exact point of suspension is noted; suppose it to be Z, the distance from X is therefore X Z. The specimen is then immersed in water, as shown in sketch, care being taken to remove by means of a brush any air-bubbles that may adhere to it, and reweighed; suppose the point of suspension now to be Y, the distance from X is therefore X Y.

Now, since as follows from the properties of a lever, the weights in air and water are in inverse proportion to the distances of the respective points of suspension from X, and since the amount lost by immersion is exactly represented by the difference between the latter, it is evident that—

$$\frac{XY}{XY - XZ} = \text{the specific gravity of the specimen.}$$

An example may perhaps show this more clearly:—Suppose that in weighing in air Z, the point of suspension is 10 inches from X, and that, on reweighing in water, Y is 15 inches from X, then by the above formula—

$$\frac{XY}{XY - XZ} = \frac{15}{15 - 10} = 3 = \text{the specific gravity of the specimen.}$$

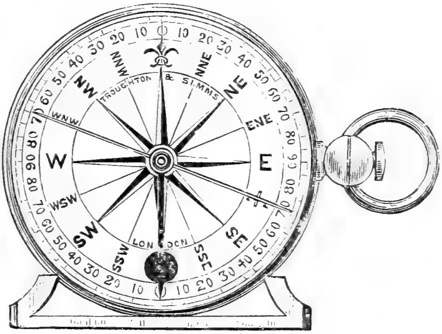
The result may be checked by changing the points of suspension of W, and then reweighing the object."

The Balance may be obtained from the maker, Mr G. Lowdon, Reform Street, Dundee.

APPENDIX E

COMPASS AND CLINOMETER

Any ordinary pocket-compass, if not too small, will serve to take the direction of dip. The one in common use by field geologists is divided into graduated quadrants. From North and South points, the figures in each quadrant run up on either side to 90. In taking an observation, allowance must be made for the declination or variation—magnetic north in these islands, at the present time, being about 20° west of true north. As all maps are constructed with reference to the true meridian, it is necessary that the dip-arrows we insert should likewise indicate true and not magnetic directions. In recording an observation of dip, we say that the direction is so many degrees west of north, east of south, north of west, and so on, as the case may be. Thus N. 25° W. means 25° west of north, and corresponds therefore to the intermediate compass-point of NNW.



Not infrequently, owing to the absence or paucity of streams, roads, fences, buildings, etc., the geologist may sometimes have difficulty in locating the position upon the map of some outcrop or other field data, which he desires to indicate. In order to do so he must of course take bearings with the compass, for which purpose such an instrument as that shown in the accompanying illustration is usually sufficient, but if great accuracy be demanded a prismatic compass will be necessary. After some little practice, however, the observer will find an ordinary pocket-compass quite good enough for all his requirements.

In the combined compass and clinometer here illustrated a pendulum hangs perpendicularly from the central point which carries the needle, and indicates the number of degrees the straight-edge or base, attached to the side, deviates from the horizontal. In the illustration the base being level, the pendulum points to zero. One advantage of this little instrument is that the straight-edge can be applied either to the upper or under side of a bed. Or if we are taking the angle of dip from a little distance, and holding the instrument between the eye and the angle to be measured, it is obviously immaterial whether the straight-edge occupies the position shown in the illustration or is inverted.

INDEX

PRINTED BY
OLIVER AND BOYD
EDINBURGH