Gordon G. Cameron
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OUTLINES OF FIELD-GEOLOGY

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OUTLINES

OF

FIELD-GEOLOGY

BY

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PREFACE

TO THE FIFTH EDITION

THIS Volume has again been thoroughly revised and brought up to date. Numerous alterations and additions have been made in it, but without altering the simple style of arrangement and treatment which was originally adopted, and which, as shown by the continued sale of large impressions, appears to have been found useful by beginners in Field-Geology.

GEOLOGICAL SURVEY OFFICE,
LONDON, *May* 1900.

PREFACE

TO THE SECOND EDITION

At the request of the Lords of the Committee of Privy Council on Education I gave, in the month of August, 1876, at South Kensington, two lectures upon geological maps and instruments of surveying. These lectures formed part of a series designed for teachers, and in illustration of the Loan Collection of Scientific Instruments at that time exhibited. Treating the subject allotted to me in what seemed likely to prove the most useful manner, I dwelt more specially upon the methods of observation requisite in ordinary field-geology; and endeavoured to show how, by the practice of these methods, geological maps and sections, representing in condensed form the facts established by field-work, could be constructed. The lectures were published in pamphlet form later in the autumn of the same year.

A large impression having been sold, and the work having been for some time out of print, the publishers asked me to allow it to be reprinted in a more permanent shape. I delayed complying with this request until I could find leisure to revise and extend the lectures. I have now entirely recast them; and, dropping the original lecture form, have thrown the matter into chapters, with distinct headings. So great have been the additions that the little volume now issued may claim to be a new and independent work. It retains, however, the unpretending elementary character of the original lectures. My aim has been to write primarily for that large and increasing body of readers who have made some general acquaintance with geology, but who, though much interested in the subject, find themselves helpless when they try to interpret the facts which they meet with in the field. The practical knowledge of which they feel the want is not indeed to be gained from books. It must be sought in quarries and ravines, by hillside and seashore. But hints regarding what should be looked for and how to set about the search may not be without some usefulness. And these it is the object of the following pages to give.

The young geologist, into whose hands this little book may fall, will therefore remember that it is not meant as a systematic text-book on geology. It presupposes him to have already read some such text-book; to have acquired a general knowledge of the scope of the science; and to have become, in some measure, familiar with the facts. Its purpose is to be suggestive to him, rather than didactic; to put him in the way of intelligently observing for himself, rather than to present him with what has already been discovered by others.

COLLEGE, EDINBURGH,
February 1879.

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CHAPTER I

INTRODUCTORY

To those who are fond of country-rambles, geology offers many attractions. Few men are so unobservant as not to be struck now and then by at least the more salient features of a landscape. Even in a flat featureless country, the endless and apparently capricious curvings of the sluggish streams may occasionally suggest the question why such serpentine courses should ever have been chosen. But where the ground rises into undulations, and breaks out into hills and crags; still more, where it towers into rugged mountains, cleft by precipices down which torrents are ever pouring, and by ravines in the depths of which hoarse streams ceaselessly murmur, one can hardly escape the natural curiosity to know something about these singular aspects of landscape, when and how they arose, and why they should be precisely as they are. For the day is now happily past when the sterner features of the land awakened only a feeling of horror; when they were styled hideous, and unsightly; when they were never visited save under the necessities of travel, and were always left behind with a sense of relief. Relics of these feelings survive to us in such phrases as wild, savage, uncouth, with which we still describe that mountain-world, once an object of awe and fear, now the centre to which a yearly increasing crowd of visitors repairs for some of the purest pleasures and most healthful recreation which this world has to afford. With the growth of an appreciation of natural scenery in all its forms, rugged as well as gentle, there has arisen also a desire to know on what causes these diversities of outline depend. We are not now content as our fathers were to accept the present aspect of a country as that which it has worn from the beginning of time. And even if no intelligible answer can be given to them, the questions I have referred to will ever and anon force themselves on our attention.

Nor is it only the larger and more impressive features of the landscape which suggest such inquiries. A boulder perched on some slope or on the edge of a crag, seemingly so perilously poised that a mere push with the hand should send it rolling into the plain below, will raise in our minds the questions why the block should have stopped where it is, whence did it come, how was it carried, and what arrested it there? On either side of a soft, well-cultivated valley we may perhaps detect, peeping out at intervals from among the woodlands, orchards, and cottages, a strong rib of rock, forming everywhere a marked feature, with its gray, lichen-crusted face, deep fern-hung shadows and tufts of sweet-briar, honeysuckle, or bramble. Its regularity of level suggests at a distance some artificial landmark—a road, or fence, or ruined rampart. Yet we see on nearer inspection that it must be a natural feature, and we ask ourselves why it should have arisen on the face of those green declivities, and why its course on the one side of the valley should be so exactly repeated on the other. Perchance a prominent mound rises from the general level of a plain, so singularly as to have attracted notice from the earliest times, and to have become the origin of a local myth. It seems too large to be due to man's operations, even if any intelligible reason could be assigned for his having heaped it together. On the supposition that it is natural, however, how are we to account for its existence? What agent could have lifted its materials and piled them up into that solitary cone?

Again, the merest fragment of stone picked up on some everyday ramble may furnish questions, for the due answering of which many years of profitable study might be needed. A piece of limestone, for example, may show us on its fractured surface abundant fragments of corals and shells. With a little inquiry it may not be difficult to ascertain the source of the stone, and to visit the rock in place. We may there find a thick bed of limestone, crowded throughout with similar organisms, and extending for miles across the country. It would need but a slender acquaintance with modern science to make us feel assured that this limestone must represent an old sea-bottom once thickly covered with living things. We might muse on the strange vicissitudes of nature, wherein the oozy floor of a former ocean has been changed into a land "made blithe with plough and harrow," and might ask ourselves how and when these revolutions were effected. In the course of another walk we might stumble upon a bit of stone made up of rounded pebbles cemented together, as if a handful of gravel from some river-side had been hardened into stone. Could we trace this fragment also to its original locality, we should find it to have formed part of a larger bed or mass of what is called conglomerate or puddingstone, and we should recognise still more the exact resemblance of the constituent stones of this rock to the shingle of a sea-shore, or the gravel of a river-bed. We could not for a moment doubt that the rock must be merely so much compacted water-worn gravel. But where lay the water by which these stones were rounded and polished? Was it the sea, or a lake, or a river? What was the aspect of the country then, and through what cycles of change has it passed to reach its present condition?

Thus even to one who knows no geology, the problems of the science are presented at every turn and in every country ramble. When, however, some acquaintance with this science has been gained, the number of questions which arise for solution rapidly increases, and with their growth there augments also the power of answering them, or at least the pleasure of seeking for their solution. The observer, as he finds his knowledge and consequently his confidence enlarged, discovers, on the one hand, that facts which he took for granted, and which never raised in his mind any question or difficulty, now demand some explanation, and, on the other, that he has to disabuse himself of many prejudices or notions which grew up in his mind, he cannot tell when or how. For example, it never used to occur to him that there was anything especially deserving of notice in the fact, that the stones of an old building have almost invariably lost their sharp edge, and in many cases are crumbling and honeycombed. But he now observes these aspects, and derives from their study another pleasure to be added to the many which an interesting ruin yields to every one. He notes what kinds of stones decay most, on which aspect of the building the weathering is most advanced, and endeavours to ascertain on what circumstances the disintegration seems to have depended. For he recognises that the walls of a building may be likened to the sides of a crag or precipice, and that in contemplating the progress of decay in a human edifice, he can learn not a little respecting the laws which govern the disintegration of the mountains. Again, he no doubt began with the common popular belief that the striking features of a landscape, notably its crags and ravines, are to be referred directly to the operation of earthquakes and of former convulsions of nature. Slowly and perhaps with some difficulty he rids himself of the incubus of this prejudice. He refuses any longer to be bound by preconceived theory or explanation, but insists on being allowed to judge of each instance on its own merits and to reason upon it with reference to all its surroundings.

If after having familiarised his eyes with the outward aspect and inner geological relations of his own district, the observer extends his journeys into other regions, he carries with him an added power of enjoyment in every country through which he may wander. He finds that an acquaintance with geology, far from blinding him to the softer beauties or wilder grandeur of a landscape, really quickens his perception of these charms. Practice enables him to take in at a glance the dominant features, and to range the others in their orderly subsidiary places, so that the harmony of the whole is seized, and the impression which it makes is fixed upon the mind. If I may be allowed to make the comparison, it is with the appreciation of scenery as with the cultivation of music. Most listeners of average education and intelligence thoroughly enjoy a sonata of Beethoven; they listen to a harmonious variety of sound, and perhaps at the close awake almost out of dreamland. And yet, high as is their enjoyment, it can hardly equal that of the musician who recognises, as movement succeeds movement, the skill and genius of the composer who could so vary and amplify some simple theme, and while seeming to abandon himself to a tumultuous torrent of sound could keep every portion of the work under the strictest rules of art, and with a breadth and harmony that bind the composition into one magnificent whole.

Should the traveller abroad find himself with leisure sufficient not merely to look at the scenery but to examine the rocks which form its groundwork, he will again find his experience at home stand him in good stead and give fresh interest to his journey. He will encounter other and often better illustrations of phenomena with which he has already become practically familiar. He will perhaps meet with facts which throw a bright light on questions that had long puzzled him in his own country. Or he may see for the first time, and with a joy which he alone can experience, an example of some piece of geological structure which he has known only from books, but which he now and for ever vividly realises.

In all this it is not needful that he should claim to be a geologist. He may not consider his observations worthy of attention from professed geologists, or he may have neither time nor inclination to publish them. But none the less does he enjoy the refreshment, alike bodily and mental, which geological work in the field brings with it. Should he, however, deem it proper to give the world the benefit of his labours, he may have the satisfaction of adding to the sum of knowledge, and of eliciting the thanks of geologists who will gladly admit him of their number. More especially he should be encouraged to publish his observations when they relate to unvisited or little known regions, or to tracts where he has enjoyed exceptional advantages for studying geological phenomena.

But how is this geological experience to be acquired? How often do we meet with men who have read extensively in geology, yet if they are set down among the rocks find themselves hopelessly adrift, and after some despairing efforts to recognise in nature what seems so clear in the diagrams of a text-book, give up the pursuit in disgust. On the other hand, how constantly are men to be encountered who labour under the delusion that nature is as easily read as the manual whose pages they have so often skimmed over, and who proceed at once to quarry, hillside, or mountain, and explain its geological features with much more confidence than those would pretend to do who have made the subject their prolonged study. It is not from books alone that a man can acquire that practical acquaintance with geology which will minister so much to his elevation and enjoyment. He must betake himself to nature from the first. His lessons in the field should accompany his lessons from the text-book or lecture-room. In many cases he must grope his way without guide or assistance. His progress will be slow, but in the end he may find that it has been none the less sure and pleasant, and that, through this very tardiness of his advance, he has been compelled to master thoroughly every foothold of the way. The following chapters are offered for his help. They are not to stand in the place of a systematic text-book, of which he will find still constant need. But still less are they to be looked at as in any way a substitute for practical observation in the field. Their aim is to point out how observations may be made, what kinds of data should be looked for, what sort of evidence should be sought to establish a conclusion, and what deductions may be drawn from particular facts. In short, they are to be regarded as sign-posts pointing out some of the highways and byways of geological inquiry, but leaving the reader to perform the journey in his own fashion. Their object will be fully realised if they induce him to find so much interest in the pursuit as to adopt it as a frequent solace for his leisure hours. But they are so arranged that it is hoped they may not be found without service to young geologists, who, whether at home or abroad, would fain devote themselves with energy to the task of geological investigation.

The term Field-Geology, which I have selected as expressive of my subject, points then, to practical work in the open field, as distinguished from the researches which may be carried on in the library or laboratory. I wish to describe some of the methods by which a geologist obtains his information regarding the nature, position, arrangement, and history of the rocks of a country. Such practical observation evidently underlies all solid research in geology. He who would pursue the theoretical parts of the science must either himself lay a foundation in good thorough field-work, or take advantage of the foundation which has, in this respect, been laid for him by others.

Field-geology may be pursued with various aims and in various ways. To some men it is little more than another name for holiday-making in the country—fresh air, healthy exercise, new or old charms of scenery, and a bag full of "specimens" to attest the scientific nature of the work. To others it is the solace and delight of busy lives, furnishing them not only with bright intervals of escape to the country, but with materials for much profitable thought and study when the ordinary duties and cares of life confine them to their work in town. To other men, again, it is itself the main occupation of life, whether they cultivate it for its own sake, or with a view to the economic applications of which it is susceptible.

There are few countries or districts where field-geology may not be cultivated, and where its healthful influence as an educational instrument may not be tested. A few days of intelligently guided observation in the field are worth far more to a pupil than many weeks of lectures and reading. But we seldom hear of such practical instruction, mainly because the teachers never received it, and have not had time, inclination, or opportunity to develop it for themselves.

PART I

OUT-OF-DOOR WORK

CHAPTER II

FIRST ESSAYS IN FIELD-WORK

THE direction in which the first essays of the observer in the field should be made, must depend mainly upon the nature of the district in which he finds himself situated. Under the most unfavourable circumstances, as for instance in a wide cultivated plain, with not a single quarry or natural opening to show even the nature of the formations underneath, he may nevertheless discover something to engage his attention. Thus, he may find useful employment in watching the operations of the streams which flow sluggishly through his neighbourhood, their meanderings and the efforts they make to straighten their courses, their varying quantity of mud, the effects of floods, the evidence of successive deposits, and heightening of the flood-plain. But it will seldom happen that he cannot in some way gain access to the geological formations below the surface, and even in a flat and featureless country obtain a series of facts which will enable him to reason as to the history of the region, and to decide whether the plain has been formed by the stream, or on the floor of some ancient lake, or perchance on the bed of the sea.

Where, however, numerous openings, either natural or artificial, expose the strata underneath, the observer need be at no loss for abundant material for profitable field-work. Should some of these strata be eminently fossiliferous, that is, crowded with the remains of once living plants or animals, they will almost certainly attract his earliest attention. Probably most people are led to the study of geology by first becoming interested in the organic remains which they can collect for themselves, carry home as "specimens," and afterwards thoughtfully question as to their structure and history. No doubt the mere gathering of fossils is the first and final achievement of a very large proportion of enthusiastic beginners. Even, however, if the pursuit has had no other advantage than that of affording ample exercise in the open air, it is perhaps not less beneficial than many of the time-honoured forms of out-of-door recreation.

But a man may gain much more than healthful amusement from fossil-hunting. He begins, let us suppose, by trying to get hold of as many varieties, and as perfect specimens as he can find by the most patient search. But the mere pleasure of the pursuit soon begets a desire to know more about the fossils. If they are plants, the collector strives to ascertain their names, and may be content perhaps if he can write upon them their proper Latin or Greek appellations. Possessed, however, of a real desire for knowledge, he seeks to ascertain what are their affinities with the living vegetation of to-day. By reading, by visiting museums, and by careful observation along the hedgerows or in botanic gardens, he endeavours to realise what the leaves and stems, which he finds in the solid stone, really were when they waved bright and green in the air long ages ago. The information he can glean as to their probable botanical grade and habit, leads him to re-examine, with greater care, the circumstances under which they lie in the rock. He finds, perhaps, that they occur more particularly in one stratum, which we shall suppose consists of thin leaves or laminæ of a kind of hardened clay. It is on splitting up these laminæ that he unfolds the fossil plants. Each layer seems entirely covered with impressions of leaves, stems, fruits, or other parts of the ancient vegetation; but the fossils are all fragmentary, though well preserved. They remind him of the sheddings of trees after some early autumnal frost; the fine layers of hardened silt, on which they lie, recall the laminæ of mud which he has observed in the bottom of a pond or dried-up pool; and in the end, he concludes with some confidence that his fossil-bearing stratum was once the floor of some inland sheet of water, into which the leaves of the neighbouring woodlands were periodically shed. If he has ascertained that the plants are more nearly allied to those of a warmer region than the vegetation now flourishing in the locality, he allows himself to speculate on the probability that a warmer climate once prevailed in his own country.

The remains of animals, however, are immensely more abundant among the rocks than those of plants. The observer is much more likely, therefore, to begin by lighting upon some stratum full of shells, crinoids, corals, or even with bones of fishes, and perhaps of reptiles. If he is not satisfied merely with forming a collection of these remains and having them rightly named, but wishes to learn what they have to tell him about ancient types of life and old conditions of physical geography, he addresses himself to the task by endeavouring to find the nearest analogies in the living world to the fossil forms which he has disinterred from the rocks. Patiently he tries to reconstruct the skeleton of which he has found the scattered bones. He learns to recognise the fragment of a shell or other fossil, and can assign it to its place in the complete organism. While the structure and zoological relations of the fossils afford him inexhaustible stores of employment, he cannot shut his eyes to the circumstances in which these fossils occur, and to the light which they cast on the history of the rocks. Corals, crinoids, and marine types of molluscan life bring before him an old sea-floor, and though the locality where his leisure hours are thus sedulously spent may now lie far in the heart of a country, with venerable trees and hedgerows, old farmsteads and roads, all bearing witness to the peaceful cultivation of centuries, the sight of that rock with its crowded fossils is as sure evidence of the former presence of the sea over the whole landscape, as if he heard there even now the murmur of the waves.

But the observer's lot may be cast in a district where no fossils are to be found. There may be nothing in the rocks themselves to attract notice, nothing likely to inspire a taste for geology or to furnish nutriment for a taste already existent. It is remarkable, however, in what apparently unfavourable circumstances an appetite for scientific pursuits can not only exist but flourish. Let us suppose that the district in question consists of stratified rocks, like sandstones and shales, and that these strata are exposed to view in numerous quarries and natural sections. The varying composition of the beds, their order of succession, their changes in character as they are traced over the country, their influence upon the contour of the ground, the glimpses they afford of an ancient geography very different from that of the district to-day, and the manner in which they have been tilted up, curved, and broken since the time of their original formation—these, and a thousand other particulars, will eventually give even barren and seemingly repulsive rocks a charm which the richly fossiliferous deposits of the observer's later experience may never possess. If, on the other hand, the rocks are crystalline —granites, schists, and other similar masses, or basalts, tuffs, and other volcanic accumulations, the geologist who begins work among them will almost of necessity devote himself to the mineralogical and structural side of the science. He may be first attracted by pretty minerals, —sparkling felspars, well crystallised and variously coloured quartzes, glittering micas, and many more. And doubtless the temptation to collect them, if it once arises within him, will not be likely to diminish, so long as his taste for geological pursuits lasts, and as he finds himself face to face with the minerals in the field. Pursued not as the hobby of a collector, but as an important branch of the sciences which deal with the architecture of the globe, mineralogy becomes a singularly fascinating study. I shall have occasion in later chapters to allude to some of its attractions. Should the observer be led from the minerals to the investigation of the rocks among which they lie, he will find himself in presence of some of the most interesting problems in geology. Some of these crystalline rocks are amongst the oldest of the globe; their origin is linked with the earth's early history, they are witnesses of the power of that internal heat which has played so notable a part in the growth of the solid land. As a rule, too, the districts where they occur are more rugged than those which the fossiliferous formations overspread: hence they may present everywhere crags, knobs, and bosses of rock, as well as the more continuous sections of water-courses. By these frequent exposures the successive bands of rock can be traced; their variations in breadth, in composition and in mineral contents can be followed; and their intercalations, curvatures, fractures, and veins, can be unravelled, so as to reveal, more or less clearly, the structural plan of a whole region.

In most places, save on the face of precipices and steep declivities, the rocks which form the framework of a country are more or less concealed by various superficial accumulations. Even should he never set himself to the study of the underlying formations, the observer may find ample scope for inquiry in these upper deposits. In one region he will encounter thick masses of earth or loam, containing here and there the bones of long extinct mammals. In another quarter he may meet with sheets of gravel, perched on the sides of valleys high above the present streams, yet evidently themselves of fluviatile origin, and containing scattered rude stone-implements of human workmanship. In yet a third locality he will find a mass of clay, stuck full of stones with their surfaces polished and scratched like the rocks below a Swiss glacier, and he will learn that these striated stones and the clay containing them have once likewise been under a sheet of ice. In short he will soon perceive that in every one of the many varieties of superficial deposits there is a story to be made out, and that it is worth his while to decipher it.

Lastly, it may chance that the beginner is so situated as to be able to watch the actual visible progress of geological changes. His home may be by the margin of a river liable to occasional floods, and always bearing onward past him its burden of mud from distant hills. No better training in geological observation could he desire than that which is supplied by a careful and methodical study of the operations of a river. Its times of flood and of low water, the proportion of mineral substances in its water from month to month, the way in which the sediment is disposed of, the action of the river on its banks, here cutting down and there heaping up, the relation of the form of the channel to the rocks through which it has been cut, now a ravine, now a waterfall, here a rapid, there a lake-like reach—these and many other points in the physics of a river furnish endless material of ever fresh interest. The stream has its moods like a living thing; no two years of its operations are exactly alike, and it seems always to have surprises in store for us, though we may have watched it for years and are familiar with it under every aspect.

Even more fortunate is the observer whose dwelling lies not only near a river but within reach of the sea. Even if the shore be low and sandy, he can watch the breakers as they come tumbling in upon the beach, and mark how the colour of the water changes as it drags back the sand in its recoil. The sight of this ceaseless grinding impresses him, as hardly any other scene can do, with the way in which boulders and gravel are reduced to the state of sand and spread over the sea-floor, there to lay the foundations of the land of future ages. But should the coast be rocky, he may congratulate himself on having been placed in a kind of geological paradise. Scarcely anywhere else will he meet with the same facilities for observation. The beach serves as a platform on which the rocks are exposed for his study, and which is swept clean for him twice every day by the tides. He may devote himself to the investigation of the rocks themselves, their contents and history, or he may observe the way in which they yield to the attacks made upon them by the sea on one side, and by the air, rain, frost, and springs on the other.

We may conclude, therefore, that there must be very few parts of the world where some kind of field-geology cannot be pursued. If the beginner who has read enough in the science to make him desirous of becoming himself an observer, finds it hopelessly impossible to extract any information or interest from his surroundings, he will probably be right in suspecting that the fault lies in himself, rather than in them. Perhaps the chapters which follow may suggest some method of overcoming his difficulty.

CHAPTER III

ACCOUTREMENT FOR THE FIELD

THE nature and extent of a geologist's accoutrements will, of course, be regulated by the kind of work he proposes to undertake, and the character of the rocks among which he is to be engaged. If his object be the collection of specimens of minerals, rocks, or fossils, he will require one sort of apparatus; if it be the study of the geological structure of the region, he will provide himself with another sort. It must be distinctly understood at the outset, that the popular idea that a geologist must necessarily be one who amasses stones and comes home with a fresh burden from every excursion, is a popular but rather mischievous delusion.

Field-geology does not mean and need not include the collecting of specimens. Consequently a formidable series of hammers and chisels, a capacious wallet with stores of wrapping-paper and pill-boxes, are not absolutely and always required. Rock-specimens and fossils are best collected after the field-geologist has made some progress with his examination of a district. He can then begin to see what rocks really deserve to be illustrated by specimens, and in what strata the search for fossils may be most advantageously conducted. He may have to undertake the collecting himself, or he may be able to employ a trained assistant, and direct him to the localities whence specimens are to be taken. But in the first instance, his own efforts must be directed to the investigation of the geological structure of the region. The specimens required for his purpose in the early stages of his work do not involve much trouble. He can detach them and carry them off as he goes, while he leaves the full collection to be made afterwards.

It is of paramount importance that the field-geologist should go to his work as lightly equipped as possible. His accoutrements should be sufficient for their purpose, and eminently portable. The reader may judge of the portability which may be secured, when he learns that he may carry on his person, at the same moment, all the instruments necessary for a geological investigation, even in the detailed manner adopted in the Geological Survey of this country, and that yet, although a fully-equipped field-geologist, he need not betray his occupation by any visible implement. The want of such tokens of his craft often greatly perplexes rustic observers to whom his movements are a fruitful source of speculation. He may find himself, for instance, taken at different times and places for postman, doctor, farmer, cattle-dealer, travelling-showman, country-gentleman, gamekeeper, poacher, temperance-lecturer, gauger, clergyman, play-actor, and a generally suspicious character. One of my colleagues in the Geological Survey, who had just taken quarters in a village, was watched for some time by the police, under the belief that he had been concerned in a recent burglary.[1]

1. *The Map.*—Unless the geological work to be done merely consists in visiting already known ground and making detailed notes, or collecting specimens there, it is of the utmost consequence to obtain as good a map of the region as can be had. Not merely does the observer find the advantage of the topographical guide over the ground, but, as I shall point out in a succeeding chapter, he cannot, in many cases, satisfactorily work out the geological relations of the rocks unless he possesses a map on which to place, in their proper geographical position, the notes he makes at each locality. Hence if he cannot procure a map, or if he is at work in a country which has not yet been topographically surveyed, he may find himself compelled to make a map for himself with as near an approach to accuracy as the means at his command will admit. This subject is further discussed in Chapter IV

2. *The Hammer.*—This is the chief instrument of the field-geologist. He ought at first to use it constantly, and seldom trust himself to name a rock until he has broken a fragment from it, and compared the fresh with

[1] On one occasion, in company with a Survey colleague, I reached a straggling village in the east of Fife, just after a travelling show had entered it. The villagers were still standing at their doors, discussing the character of the new arrival, when we passed them. Of course we were naturally supposed to form a kind of rear-guard of the cavalcade; but we had the satisfaction of hearing one old woman remark to her neighbour, as we brushed past them, "Na, noo, arena' thae twa decent-looking chields to be play-acting blackguards?"

the weathered surface. Most rocks yield so much to the action of the weather as to acquire a decomposed, crumbling crust, by which the true colour, texture, and composition of the rock itself may be entirely concealed. Two rocks, of which the outer crusts are similar, may differ greatly from each other in essential characters. Again, two rocks may assume a very different aspect externally, and yet may show an identity of composition on a freshly-fractured internal surface. The hammer, therefore, is required to detach this outer deceptive crust. If heavy enough to do this, it is sufficient for the purpose; any additional weight is unnecessary and burdensome. A hammer, of which the head weighs one pound or a few ounces more, is quite massive enough for all the ordinary requirements of the field-geologist. When he proceeds to collect specimens he needs a hammer of two or three pounds, or even more, in weight, and a small, light chipping hammer, to trim the specimens and reduce them in bulk, without running a too frequent risk of shattering them to pieces.

Hardly any two geologists agree as to the best shape of hammer; much evidently depending upon the individual style in which each observer wields his tool. This (Fig. 1) is the form which, after long experience, we have found in the Geological Survey to be on the whole the best. A hammer formed after this pattern combines, as may be observed, the uses both of a hammer and a chisel. With the broad, heavy, or square end, we can break off a fragment large enough to show the internal grain of a rock. With the thin, wedge-shaped, or chisel-like end, we can split open shales, sandstones, schists, and other fissile rocks. This cutting or splitting edge should be at a right angle to the axis of the shaft. If placed upright or in the same line with the shaft, much of its efficiency is lost, especially in wedging off plates of shale or other rocks.

A hammer, shaped as I recommend, serves at times for other than purely geological purposes. On steep grassy

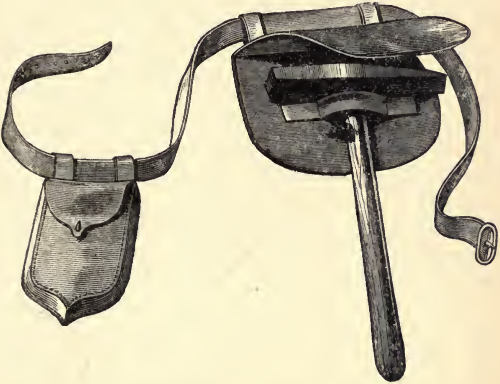


FIG. 1.—Geological hammer, compass-case, and belt.

slopes, where the footing is precarious, and where there is no available hold for the hand, the wedge-like end of the hammer may be driven firmly into the turf, and the geologist may thereby let himself securely down or pull himself up.

The most generally convenient way of carrying the hammer is to have it in a leather sheath suspended from the waist-belt. The hammer hangs at the left side under the coat, the inside of which is kept from being cut or soiled by the protecting outer flap of the sheath. Some geologists prefer to carry the belt across the shoulders outside, and the hammer suspended at the back. Others provide themselves with strong canvas coat-pockets, and carry the hammer there.

3. *The Lens.*—Even the most sharp-sighted observer is the better of the aid supplied to him by a good magnifying-glass. For field-work a pocket lens with two powers is usually sufficient. One glass should have a large field for showing the general texture of a rock, its component grains or crystals, and the manner of their arrangement; the other glass should be capable of making visible the fine striæ on a crystal, and the minuter ornament on the surface of a fish-scale or other fossil organism. A platyscopic lens, combining the advantages of a wide field with strong magnifying power is a most useful instrument. Applied to the weathered crust of a rock, a lens often enables the observer to detect indications of composition and texture, which the fresh fracture of the rock does not reveal. It sometimes suffices to decide whether a puzzling fine-grained rock should be referred to the igneous or the aqueous series, and consequently how that rock is to be coloured on the map.

4. *The Compass.*—Any ordinary pocket compass will suffice for most of the requirements of the field-geologist. Should he need to take accurate bearings, however, a small portable azimuth compass will be found useful. This is the instrument employed in the Geological Sur-

vey. It may be carried in a leather case or pocket hung from the waist-belt, on the side of the body opposite to the hammer. (Fig. 1.) The directions of the dip and strike of rocks, the trend of dislocations and dykes, the line of boundaries, escarpments, and other geological features are observed accurately, and noted on the spot at the time of observation, either upon the map or in the note-book. A convenient instrument for light and rapid surveys, or reconnaissances, combines the compass and the next instrument I have to describe—the clinometer. I shall refer to it again.

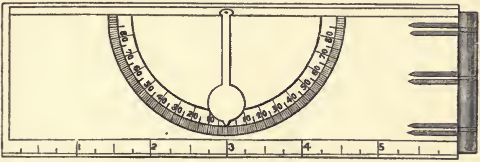


FIG. 2.—Clinometer.

5. *The Clinometer*, or dip-measurer, is employed to find the angle at which strata are placed to the horizon—an important observation in the investigation of the geological structure of a country, and one having frequently a special economic value, as, for instance, when it points out the depth to which a well or mine must be sunk. Various patterns have been proposed and used for this instrument. Formerly a spirit-level was commonly employed, and no doubt for purposes of extreme accuracy it is desirable. But apart from the difficulty of rapid adjustment for the requirements of the field, the spirit-

levels in the clinometers were apt to get broken. A much more portable and serviceable form of clinometer may be made by the geologist himself. It consists of two thin leaves of wood, each two inches broad and six inches long, neatly hinged together, so as to open out and form a foot rule when required. On the inside of one of these leaves a small brass pendulum is so fixed that when it swings freely and hangs vertically, it forms an angle of 90°, with the upper edge of the leaf to which it is attached. An arc, graduated to 90° on each side of the vertical, is drawn on the wood, or on paper or brass fastened to the wood, so that when the leaf is moved on either side, the exact number of degrees of inclination is shown by the pendulum on the graduated arc. The corresponding face of the opposite leaf is hollowed out just enough to let the two leaves fit closely, and keep the pendulum in its place when the instrument is not in use. This form of clinometer, made of boxwood and bound with brass, may be obtained of instrument makers.[1] It is light and strong, and its durability may be understood from the fact that the instrument which I carry in the field has been in use for more than forty years.

If at any time the geologist has occasion to lighten his equipment for some long mountain expedition, where every additional ounce of weight begins to tell by the end of the day, and where, therefore, for the sake of doing as much and holding out as long as possible, he

[1] This and the other instruments referred to in the text may be obtained from Troughton and Simms, London; Turnbull and Co., Edinburgh; Robinson and Sons, Dublin; or from any of the numerous dealers in minerals now to be found in this country and abroad.

should carry nothing that is not absolutely needful for his purpose, he may advantageously combine the pocket-compass and clinometer, in the one instrument to which I have already alluded. This convenient instrument is about the size of an ordinary gold watch. It consists of a thin, round, flat metal case, shaped like that of a watch, and covered either with a common watch-glass, or still better, with a flat disc of strong glass. Instead of figures for the hours and minutes, the white enamelled face of this geological watch is that of a common pocket-compass. But the interval between each of the four cardinal points is divided into 90°. On the central pivot, just underneath the needle, a small brass pendulum is placed, and a straight-edge of metal is soldered on one side of the outer rim of the watch-case in such a position that the instrument will stand on it if need be, and the pendulum will then point to zero. A simple piece of mechanism passing through the handle enables the observer to throw the needle off the pivot, or let it down, as he may require.

6. *The Note-Book and Pencils.*—As it is impossible for a field-geologist to remember the details of all the observations he makes on the ground, or to insert them on a map, he regards a good note-book as an essential part of his apparatus. From the nature of his work he has frequently occasion to make rough sections, or diagrams, and if possessed of the power of sketching, he has abundant opportunity of aiding the progress of his researches by jotting down the outlines of some cliff, mountain, or landscape. Hence his note-book should not be a mere pocket memorandum-book. A convenient

size, uniting the uses of a common note-book and a sketch-book, is seven inches long by four and a quarter inches broad. Where geological exposures have to be carefully sketched to accurate scale it is desirable to make use of paper ruled into squares. Two sets of lines, expressed either by a water-mark in the paper or by coloured ruling, cross each other at right angles and the squares thus produced serve for inches, feet, or yards, as the observer may choose. With a foot-rule or tape-line he measures the proportions of his section, and has no difficulty in plotting these accurately on his ruled paper.

Let me remark in passing that perhaps no accomplishment will be found so useful by the field-geologist as a power of rapid and effective sketching from nature. If he has this power in any degree, he ought sedulously to cultivate it. Even though he may never produce a picture, he can catch and store up in his note-book impressions and outlines which no mere descriptions could recall, and which may be of the highest value in his subsequent field-work. This is true of ordinary detailed surveys, and still more of rapid reconnaissances which may have their ultimate usefulness enormously increased if the observer can seize with his pencil and carry away the forms of surface as well as the geological relations of the region through which his traverse lies.

Photography may now be advantageously enlisted in the service of field-geology. Cameras are so portable and inexpensive, and the use of gelatine films has made them so light, that the observer may, without greatly burdening himself, add one to his equipment. Even the smallest plates, if sharp in definition, may be of extreme geological value, as they can easily be printed on an enlarged scale. The minute details of a natural or artificial section of rocks can be obtained by photography in a way which no hand-sketch could equal, save with a great expenditure of time and labour. The great defect of a photograph for geological purposes arises from the equal prominence assumed by essential and non-essential details, insomuch that the geologist himself may hardly be able to distinguish them on his prints, especially a few days or weeks after he has been to the place. In such circumstances, it is quite allowable for him to aid his work by marking off the structures on the actual rocks before he begins to photograph them. For example, he will sometimes find that a bucket of water dashed over the section will bring out the points of which he wishes to obtain a faithful record. Suppose that two rocks which he wants to distinguish are so like each other in tone that they will be sure to be merged into one in the photograph. He can sometimes make their boundary-line distinct by here and there rubbing one of them with a stone, so as to remove its coating of lichen or weathered crust, or by using a bit of white chalk either to mark a line or to put letters or numbers on the several parts of the section. Practice will soon teach him how to combine clearness and fidelity with due respect to the preservation intact of the geological and artistic features of crag, ravine, sea-cliff, or quarry.

As every device which saves labour and time in the field, or which adds to the clearness of the work, is deserving of attention, I would refer here to the use of variously-coloured pencils for expressing at once, upon map or note-book, the different rock-masses which may occur in a district. Water-colours are of course ultimately employed for representing the geological formations on the finished map. But a few bits of coloured pencils carried in his pocket save the geologist much needless writing in the field. To a red, blue, green, or yellow dot or line he attaches a particular meaning, and he places it on his map without further explanation than the local peculiarities of the place may require.

Such are the few prime instruments required in field-geology. We may add others from time to time, according to the nature of the work, which in each region will naturally suggest the changes or additions that may be most advantageously made. A small protected bottle of weak hydrochloric acid, or some powdered citric acid, is sometimes of use in testing for carbonates, particularly in regions where rocks of different characters come to resemble each other on their weathered surfaces. When Sir William Logan was carrying on the survey of the Laurentian limestones of Canada, he received much help from what he called his "limestone spear." This was a sharp-pointed bit of iron fixed to the end of a pole or a walking-stick. He enlisted farmers and others in his operations, instructed them in the use of the spear, and obtained information which gave him a good general notion of the distribution of the limestone. The spear was thrust down through the soil until it struck the rock below. It was then pulled up, and the powder of stone adhering to the iron point was tested with acid. If, after trying a number of places all round, the observer uniformly obtained a brisk effervescence when the acid drop fell on the point of his spear, he inferred that the solid limestone existed below, and noted the fact on his map accordingly.

When the Geological Survey was busy with the great Wealden area of the south-east of England, my colleagues used what they nicknamed a "geological cheese-taster." It was indeed a kind of large cheese-taster, fixed to the end of a long stick. This implement was thrust down, and portions of the subsoil and of the clays or sands beneath were pulled up and examined. Similar devices must obviously suggest themselves according to the nature of the work in different districts and countries.

In the course of his observations in the field the geologist will meet with rocks, as to the true nature of which he may not be able to satisfy himself at the time. He should in such cases detach a fresh chip from some less weathered part of the mass and examine it further at home. Detailed methods of investigation, which may be pursued with all the conveniences of a laboratory in town, are not possible to him in the country. But he may subject his specimens to analysis in two ways, and obtain valuable, and perhaps sufficient, information as to their characters. He can easily fit up for himself a small and portable blowpipe box, apparatus for preparing rocks, minerals, and fossils for examination, and a microscope with which to examine them. In Part II. of this little volume I shall enter into some details regarding these indoor employments of the field-geologist, and show how the apparatus may be put to practical use.

7. *The Blow-pipe Box* should contain as much of the most useful apparatus as space will admit, consistently

with the whole box being easily portable. The reader will find a list of the more essential articles in Chapter XVI. By means of the blow-pipe it is often possible to determine the nature of a doubtful mineral or rock, and to ascertain the proportion of metal in an ore. A young geologist should begin by taking with him to the field only the most essential apparatus and re-agents; he will gradually come to see by practice what additions he may best make to his equipment. Details on this subject will be found in Chapter XVI.

8. *Rock-slicing Apparatus.*—Portable forms of slicing and polishing machines are now to be procured, though even the lightest of them add considerably to the traveller's baggage. The field-geologist may succeed, however, in preparing his slices by chipping thin splinters from the rock and reducing them in the manner described in Chapter XVII, where instructions are given which it is hoped will enable him to supply himself with a microscopic slice of any rock he may encounter in the field. The labour involved in this process is well bestowed, for by means of the microscope, more than by any other method, he obtains an insight into the internal texture and arrangement of the rocks with which he is dealing. He sees what are the component minerals of a rock, and how they are built up to form the mass in which they occur. He likewise can detect many of the changes which these minerals have undergone, and he thus obtains a clue into some of the metamorphic processes by which the rocks of the earth's crust have been altered.

9. *Microscope.*—This instrument should be, like the rest, as portable as possible. For most purposes of field-

geology high powers are not required, consequently a small microscope is sufficient. Two powers 1½ and ½-inch focal length are extremely useful, and for the requirements of work in the field are quite adequate. An instrument with fairly good glasses of these powers, magnifying from 30 to about 300 diameters, according to the arrangement of object-glasses and eye-pieces, may be had of some London makers for £5. If more precise and detailed petrographical determination is desired, the best microscope that the geologist or petrographer can obtain is that devised by Mr. A. Dick, and manufactured by Swift and Son, Tottenham Court Road, London. The great advantage of this instrument is its avoidance of the trouble of "centering," and the consequent rapidity and ease with which it can be adjusted. The price of the stand, without objectives, is £18.

It is sometimes of service, when working in a district where microscopic rock-sections are required, to carry a small collection of microscopic slices of selected or typical minerals or rocks, for purposes of comparison. A series of fifty or one hundred slices can be packed in a box a few inches square.[1] Much assistance may be derived from the study of a collection of minute grains of minerals, obtained by reducing rocks to powder (see *postea*, p. 236).

[1] Typical series of this kind may be had from Fuess, of Berlin, or from Butler, London; or Turnbull and Co., Edinburgh.

CHAPTER IV

GEOLOGICAL MAPS

In the foregoing list of a field-geologist's accoutrements, the map was put first. The propriety of assigning it this place of honour will be admitted when the real meaning and importance of a geological map are recognised, and when the observer can carry with him the map on which he himself has traced the geological boundary-lines. A published geological map is a valuable guide when it can be had, but in the field-geologist's eyes its importance is but secondary compared with the map which contains perhaps the substance of his work for weeks or months together.

The results obtained by the geologist in the field, from his investigation of the rocks, may be set down either in writing, or in maps and sections. No one can follow the practical pursuit of the science without being conscious how much his work gains in precision when he is compelled to put it down upon a map. Not only is his information made more accurate, when he requires to trace the exact lines of geological boundary, but he is led to search in nooks and corners, of which he would not otherwise have suspected the existence, and thus he acquires a thoroughness of grasp attainable in no other way. The best field-geology is of that kind which careful and minute map-making requires. It is not, of course, imperative that an actual survey should be made by the geologist; but he must proceed in such a way that his observations, if tabulated and placed upon a map, would make that map a good geological one.

Since, then, the kind of work required in the preparation of geological maps illustrates most completely the nature and methods of field-geology, I shall describe the construction of these maps as practised in this country. The reader will bear in mind that, though he may never draw a geological boundary-line, nor take any part in a geological survey, he cannot attain excellence in the practical pursuit of geology in the field, without going through the training which, if need be, would qualify him for becoming a professional geologist. How this should be the case will, I hope, become clear in the sequel.

Let us first consider what a "geological map" is. The meaning now attached to this term differs very much from that with which it was associated not very many years ago. In the early days of geology, those who devoted themselves to this branch of science were mineralogists, rather than what we should now call geologists. They termed their subject "geognosy," meaning thereby to indicate their object to be the increase of their knowledge of the minerals and rocks of the earth. They constructed what they called "geognostical maps," on which the positions of marked varieties of minerals and rocks were shown, but without any attempt at accurate, or even sometimes approximate, boundary-lines, and with no hint whatever of geological structure, which we now regard as one of the chief objects of geological maps.

A perfect geological map should represent—1st. A full and accurate topography, with the form of the surface and heights in contour-lines, shading, or otherwise. The Ordnance Survey maps of Britain on the scale of six inches to a mile may be taken as an admirable example. 2d. All geological deposits, from the most recent to the most ancient, which may occur at the surface in the district, with their mutual boundary-lines accurately traced, and the relation of their distribution to the external form of the ground clearly depicted. 3d. The geological structure of the region, that is, the relation of the rocks to each other, their inclination downwards from the surface, their curvatures and dislocations; in short, all particulars necessary to enable a geologist to apprehend the manner in which the rocks of the crust of the earth beneath the region in question have been built up. 4th. Information which may have special economic value, such as the nature and distribution of the soils, the position of available building materials, the direction, thickness, and extent of ores, coal-seams, or other useful minerals, the best sources of water supply, etc.

To fulfil these various requirements the map must evidently be on not too small a scale. If the scale is small, the attempt to crowd a great deal of information into the map may result in confusion of detail, and much of the beauty and usefulness of the work may be lost. In such cases it is better, where practicable, to subdivide the labour, putting the older geological formations on one copy of the map, the superficial accumulations and soils on another, the industrial information on a third, and so on. But without attempting to express all the detail possible, we may construct a correct and serviceable geological map of a district or country by generalising the information, so as to give at a glance a broad and clear view of the distribution of the formations and the chief points of geological structure.

The Geological Survey of Great Britain and Ireland is constructed chiefly upon field-maps (Ordnance Survey) on the scale of six inches to the British statute mile, or $\frac{1}{10560}$ of nature, but some limited districts, where great detail is required, have been surveyed on the scale of twenty-five inches to the mile. The information is published on the scale of one inch to the mile, or $\frac{1}{63360}$, and on a reduced general map of four miles to an inch, or $\frac{1}{253440}$. A convenient scale for a generalised map of a country is ten miles to an inch or $\frac{1}{633600}$. The smaller the scale the less detail is possible, and the more care must be taken to select geological features of prime consequence.

More important than the scale is the correctness of the topographical map which is to serve as the basis of the geological one. Unless the geography be accurately depicted, geological lines may be distorted, sometimes to an extent which seriously interferes with the value of the map. The importance of this point will be understood from two diagrams (Fig. 3), which represent the influence of correct and incorrect topography upon geological lines. It will be observed that the same district is represented in both drawings; the streams and their tributaries are the same in both, but differ considerably in direction. A geologist trusting to the map A inserts the boundary-lines between the formations 1, 2, 3, 4, and 5, guiding himself

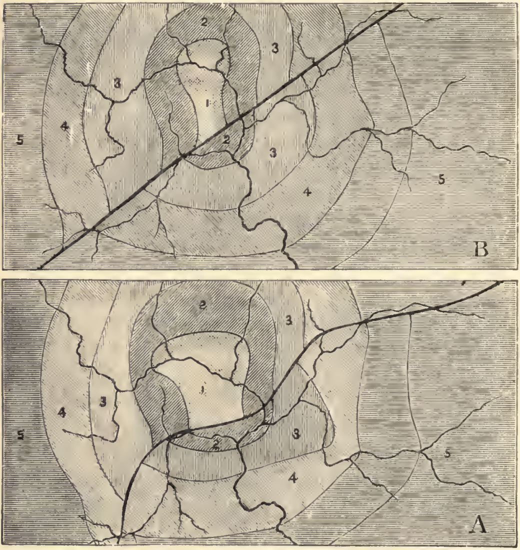


Fig. 3.—Maps showing the effect of incorrect topography in distorting geological lines.

by the points of intersection of the different streams. If now he were to trace these same lines on a map with the correct topography, as shown in B, he would find them to present considerable differences from those on A, although crossing each stream at the same points on each map. In A his thick black line is a winding one, in B it is nearly straight. Should this boundary be a line of dislocation, the reader will see that by the one map he might be led to speculate upon a sinuous dislocation, in the other on a straight one.

In Europe, geologists can generally obtain accurate maps on various scales, which, by supplying a good topographical basis, enable them to reach any degree of finish and completeness in geological map-making. It is useful, however, to be able to construct one's own rough field-map, or to correct a faulty one. For this purpose we avail ourselves of the ordinary methods of triangulation. We may measure, as accurately as practicable, a base-line along some level piece of ground, such as a river-meadow or a sea-shore. From each end of our measured line we take a bearing with an azimuth compass to some neighbouring object. The point of intersection of the lines of these two bearings gives the position of the object on the map. Having one or two triangles constructed in this way, we may continue triangulating the whole district and filling in the topography, so as in the end to produce a map which, though not quite accurate indeed, will probably serve our immediate purpose.

In those parts of the world where no good maps yet exist, geological and topographical surveying are sometimes conjoined. I may cite, as admirable illustrations of this union, the explorations of the river-courses of Canada by Sir William Logan, first Director of the Canadian Geological Survey. He and his colleagues had to furnish themselves with canoes, attendant Indians, provisions, and hunting-gear, and push up unexplored rivers, winding through the dense forests of the province. They explored, mapped, geologised, and hunted, laying down lines of traverse which served as the base for future more detailed topography, and did vast service in opening up the country. Still more elaborately topographical were the remarkable surveys and reconnaissances by Dr. F. V. Hayden, Geologist in charge of the Geological and Geographical Survey of the Western Territories of the United States. Year by year valuable reports, drawings, and photographs by that able observer and his associates made known the geography, geology, natural history, botany, meteorology, ethnology, and antiquities of thousands of square miles of previously unexplored or but partially explored land.

Having obtained or made as good a topographical map as may be attainable for his purpose, the observer is furnished with the first great requisite for geological surveying, and one of the most useful parts of the equipment of a field-geologist, whether he attempts any actual surveying or not.

Next to accuracy, judgment, and patience, neatness of hand is desirable in the geologist who would work out the structure of a district and express that structure on a map. Even the largest scale map does not admit of very voluminous notes upon its area, and where the scale is small there may be no room for notes of any kind. Under these circumstances the observer will do well to practise with the finest point to his pencil, making the neatest and most legible writing. After a brief experience he will find that he necessarily adopts a system of signs and contractions on his map, not only to save writing, but to prevent the map from being so overcrowded with notes as to become hopelessly confused. Every field-geologist insensibly invents contractions of his own. For the fundamental facts of geological structure, however, it is eminently desirable that the same signs and symbols should be used with the same meaning on all published geological maps. The subjoined diagram shows some of the signs used on the maps of the Geological Survey of Great Britain and Ireland.

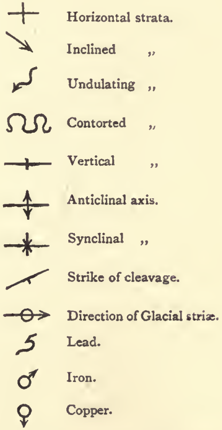


FIG. 4.—Some useful signs in geological surveying.

CHAPTER V

PRELIMINARY TRAVERSES OR RECONNAISSANCES—CIRCUMSCRIBING CONDITIONS

Having now examined the various parts of the equipment of a field-geologist, let us proceed to notice what use he must make of them. At the outset I would remark that while the mere possession of good instruments cannot make a geologist, the want of them will not prevent a skilled geologist from doing good work. The training of years enables him to judge of rocks and angles, of dip and of trends of boundary so nearly accurately as to make him often independent of hammer, compass, and clinometer. In like manner long experience quickens his eye to detect geological evidence where a less practised observer, though searching for information, would fail to find it. This difference of training tells greatly in all preliminary surveys, reconnaissances, or rapid traverses of a country. The geologist who has already had many years of campaigning carries with him a faculty of grasping the salient features of geological structure, and directing his attention, on the march, to every available source of information which will help him to fill in the details of his section. If it were always practicable, the exploration of new regions, where the traveller is necessarily confined to his line of route, but where he has nevertheless to report on the geology of many thousands of square miles of territory, should be placed in the hands of men trained in geological surveying. That this arrangement would be of advantage will be, I think, admitted, when we have entered a little more into the details of field-work.

No questions are probably put so frequently to the field-geologist as these—"How do you know what lies beneath the surface soil? Do you dig or bore?" When he replies that he neither digs nor bores, yet can usually infer with considerable confidence what must be the nature of the rock underneath, his statement is received with a look of bewilderment or a half-incredulous smile. But though the geologist does not usually dig or bore, he avails himself of every artificial opening that offers information with regard to the rocks beneath the surface. Every natural exposure of rock comes under his notice. If there is a coast-line, he makes a preliminary traverse of it, to ascertain the general nature of the rocks. He ascends one or more of the stream-courses for the same purpose. If there is any commanding hill in the district, he makes an early excursion to its top, that he may gain some general idea of the form of the ground and the probable distribution of the geological formations, so far as may be indicated by the landscape. On such occasions he will find the very great advantage of being able to sketch in his note-book an outline of the landscape. By so doing, he fixes the features in his mind in their natural proportions; he has the original sketch to refer to and to recall impressions which cannot be preserved by written words; and he has his attention drawn to those prominent features where probably he may meet with most interesting and profitable geological work. First jottings of this kind in a country never before visited, and of which the geological structure is still unknown to the observer, have for him a special interest and value. They retain for him the natural effect made on his eye and mind by the scenery, apart altogether from any explanation he may eventually be able to offer of the meaning of the features which he impartially sketches. With increasing experience of geological structure and practice in sketching it, these rapid drawings or notes gain in precision and fulness.

At first, of course, the observer may expect to meet with innumerable difficulties in his traverses of a country. He may find it impossible to take in any general conception of the whole region; everything seems lost perhaps in endless multiplicity of detail. But as he masters the detail, his power of grasping, at an early period in the examination of a district, the salient features of the geology, will steadily increase. In particular, he will be gratified to discover that he can, with growing success, identify rocks and formations even from a distance by their outlines, colour, character of vegetation, or other distinctive trait. His first surmises regarding the geological structure of the ground, made during his preliminary excursions, will thus come to be more and more sustained by his subsequent surveys. In later chapters it will be seen by what steps he may most profitably acquire this kind of experience.

The nature and conduct of these preliminary examinations not only vary with the character of the geology and physical features of the country, they differ according to the extent to which the country is settled and populous, or trackless and unexplored; according to the existence or absence of maps of the region to be examined; according to climate and other obvious causes. Such peculiarities as these, which greatly affect the first general traverses of a country, are apt to influence all the subsequent more detailed work.

As an illustration of the different conditions under which field-geology may be carried on, let me contrast the work of the Geological Survey of Great Britain and Ireland with that of the first cartographic examination of an unexplored region like that of parts of the Western Territories of the United States. In a long-settled and populous country, such as Britain, there are abundant means of communication by road, railway, or steamboat between all or almost all districts. Villages and towns are scattered so numerously over the land that we seldom need be in any doubt as to obtaining good quarters. The penny-post and electric telegraph accompany us even into some of the most retired spots. Books, specimens, and instruments can be sent to us at a few days' notice. Of every district in the British Islands we may procure detailed Ordnance maps, by which to make our way over the ground, and on which to place the results of our geological observations. Besides, the main features and much of the detail of British geology are already known, and have been expressed with more or less precision upon published geological maps. We cannot, therefore, begin anywhere in this small country without some kind of general knowledge about the formations and structure of the district we may propose to examine.

There is still another element to be taken into account as determining the character and methods of field-geology in Britain—one which perhaps geologists themselves hardly sufficiently recognise—the climate of the country. I do not believe that any one who has not daily occasion to be out for many hours in the open air, and whose avocations make him to some extent dependent upon the weather, can have any proper notion of how good the average weather of this country is, and how few thoroughly bad days there are in the year when he cannot secure even an hour or two of outdoor exercise. Our summers are seldom too hot to prevent the full use of a long July day. Our winters are so mild, and in many seasons bring so little snow, that if need be we may in most years carry on field-work up to the end of December, and renew it at the beginning of January.

Such being the conditions under which field-geology may be prosecuted in Britain, it is evident that an observer may start for any district of the country alone and investigate its structure by himself. There is no occasion for combining a geological party, though that may be done if need be. In the organised field-work of the Geological Survey each officer has his own area assigned to him, and works out its geology himself, consulting, of course, from time to time his colleagues, who may be stationed in adjoining tracts, and arranging with them as to the joining-up of their various geological boundary-lines.

The extent of ground which can be examined and mapped in a year by one of the geologists of the Survey varies with the capacity of the surveyor; with the nature of the ground, whether level, easily traversed, and revealing comparatively few geological sections, or rough and high, laborious to climb or cross, and abounding in ravines and crags, all of which must be examined; and with the simplicity or intricacy of the geological structure and the number of boundary-lines that require to be traced. A man might complete the survey of half a county lying upon the Chalk of the south-east of England before another could get over more than a part of a single parish in such intricate geological and rough mountainous ground as that round Snowdon, or that in the west of Sutherland and Ross-shire.

Let me place before the reader some statistics respecting the rate of work in the Geological Survey of Scotland, where much of the ground is hilly and where the geological structure is often far from simple. The average annual area of ground geologically examined and surveyed by each officer in the Lowlands was not much below 100 square miles. This amount was performed by an average daily walk of from ten to fifteen miles, exclusive of Sundays, holidays, wet days, and the time spent indoors in reducing the field-work and preparing it for publication. The part of the year devoted to actual surveying may be set down as about 200 days, or it may be perhaps rather more than that. We see, then, that in the more level tracts of the country one of the members of the Scottish Geological Survey had to walk about 2000 or 2500 miles in the course of the year. Every square mile of his completed map represents, therefore, on the average, about twenty or twenty-five miles of actual walking. It is useful to measure the length of boundary-lines traced in each square mile surveyed, as we thus obtain a kind of measure of the intricacy of the work. In comparatively simple ground the ratio between area mapped and boundary-lines drawn may average about 1 to 3 or 4; that is to say, every square mile surveyed involves the tracing of three or four miles of boundary. In the Highlands the annual average of square miles surveyed is considerably less, but the intricacy of the geological detail and the physical difficulties presented by the ground are incredibly greater. The climate, too, presents serious drawbacks in its wetness and storms; and the working season is much shorter than in more genial parts of the country. So complicated is the geological structure in some parts of the Highlands that the ratio between area and boundaries rises to as much as 1 to 17 or more, each square mile examined requiring 17 or more miles of boundary to be traced.

It will be readily believed, that with all the advantages for field-geology in Britain it should be possible here to construct the most elaborate geological maps. I would refer to some of the published sheets of the Geological Survey of the United Kingdom for an illustration of what can be, and has been, done in this respect. I do not suppose that any such detailed geological work has been elsewhere attempted. The large maps on the scale of six inches to the mile, with which the field-work is now chiefly conducted, admit of almost unlimited detail. Every important or interesting stratum may be put down and traced on these maps; little dislocations of only a few feet in extent may be shown even when they are pretty closely crowded together; no feature of geological value need be omitted for want of space to express it. As illustrations of intricate and detailed geological mapping I may cite Sheets 19, 75, 96, and 101 of the one-inch Geological Survey map of England and Wales; and Sheets 14, 15, 22, 23, 91, 101, 107, and 114 of Scotland. The six-inch maps of the coal-fields, published by the Survey, should also be examined.

Now with field-geology and map-making as possible, and as actually accomplished, in Britain, let us contrast the conditions under which work of this kind must be carried on in an unexplored region like the Western Territories of the United States. The survey of vast tracts in those parts of the North American continent by Hayden, King, and Powell proved them to be among the most zealous, active, and efficient geologists who ever undertook the task of pioneering through a new country. But the utmost skill and experience cannot alter the natural features of a country and its climate. These American surveys had to be carried on in a very different manner from those of the British Isles, and I cite them as an excellent example of how field-geology can be prosecuted in new and previously unmapped regions.

As the topographical map of the country required to be made, Dr. Hayden's survey was at once geographical and geological. His staff contained more topographers than geologists. It required division into separate working parties, to each of which a distinct tract of country was assigned. From the higher hill-tops triangulations were made and outline-sketches were taken, so that a general map was traced and filled in. In this work the geologists co-operated, indicating to their associates the salient geological features of each region, and inserting these upon sections or diagrams, which, for beauty and effectiveness, are among the most remarkable geological sketches which up to that time had been produced.

Besides the scientific staff, however, provision had to be made for a foraging department; and sometimes, also, an escort was needed, where the work lay in or near the territories of hostile Indians.

As a sample of the equipment of Dr. Hayden's survey I may cite a few particulars from his Report for 1874. The staff in the field was divided into seven parties. Of the organisation of these, the first may be taken as a type. It consisted of one assistant geologist as director, two topographers, two meteorologists, one botanist and collector, one general assistant, two packers, cook, and hunter. It would seem that there was thus only one geologist in the party, though probably one or two of the other members were able to lend him some assistance. Starting on the 20th of July, the party continued the campaign till the 27th of November. During that time it surveyed 4300 square miles of new ground, which is an average of somewhere about forty square miles a day. This working party, therefore, though probably not much more than one geologist strong, accomplished in one or two days as great an area of map-work as one of my colleagues finds it possible to complete in a year. Such rapid surveying could of course be regarded as furnishing merely a kind of rough preliminary sketch of the geology of the territories, to serve as the basis for subsequent detailed surveys. It may be taken as an example of broad generalised field-work on the one hand, while the Geological Survey of Britain stands at the opposite extreme, as a model of patient and elaborate detail.

The student may usefully refer to other examples of such pioneering geological exploration in Western America. Of these, the *Exploration of the Fortieth Parallel*, under Mr. Clarence King, and the *Geological and Geographical Survey of the Rocky Mountain Region*, under Major Powell, well deserve perusal. The more recent memoirs, reports, and monographs of the United States Geological Survey and those of the Geological Survey of Canada may also be profitably studied. The "folios" of the United States Survey are particularly deserving of attention. Each of them contains a series of maps representing the topography, geology, or other features of a particular region, together with geological sections and some pages of descriptive letterpress.

Intermediate between the minutely detailed work of the British Survey and the broad outlines of the early American explorers come the geological maps published by different governments in Europe. The *Carte Géologique detailée de la France* is a good example which, with its explanatory *Bulletins*, may be advantageously consulted. Some of the most striking maps and sections of the European continent are those prepared by the Geological Commission in Switzerland. Nothing more admirable in geological illustration has ever been issued than the sectional views of mountain structure prepared by the President of the Commission, Dr. A. Heim. They combine beauty of artistic sketching with ample indications of geological structure. The *Beiträge* or explanatory volumes that accompany the Swiss maps contain a mine of geological information. The geological surveys of Prussia and Saxony are likewise worthy of the student's attention as examples of map-making, while their accompanying explanatory texts are good illustrations of geological description.

CHAPTER VI

DETERMINATION OF ROCKS

WHETHER field-geology is to be carried on rapidly and in a generalised way, or slowly and in detail, the same methods must be followed. I have supposed the geologist to have selected and reached his ground, and to have made a few preliminary traverses to gain some notion of the chief rocks and their arrangement. Let us follow his subsequent operations.

The brooks, ravines, sea-coasts, hillsides, valleys, and mountains, the pits, quarries, and railway-cuttings, in short every natural section or artificial exposure of the rocks, will be carefully examined, and the observations made will be registered in notebook or map at the time. In the course of these rambles three points will have to be settled: first, the lithology and distribution of the rocks; second, their probable or actual geological horizon or date; third, their position with regard to each other, that is, the geological structure of the district.

The determination of the nature of the rocks is obviously the first question which must be dealt with. And here it must be remembered that the term rock is applied in geology indifferently to all kinds of naturally-formed stones or deposits, even to peat, blown sand,

and mud. Taking them in this wide sense, the geologist considers, with regard to those he encounters in the field, whether they are Fragmental, Derivative, or Stratified (*Clastic*), and, if so, whether they are conglomerates, sandstones, shales, clays, limestones, ironstones, or other varieties of this great series; whether, on the other hand, they are Crystalline or Igneous rocks, and if so, whether they should be classed as granite, syenite, diorite, andesite, basalt, gabbro, serpentine, or other species of this family; or whether they are to be called Foliated or Metamorphic rocks, such as gneiss, micaschist, or hornblende-slate. To be able to answer these questions, the observer must have trained his eye by the examination of good typical specimens of rocks. This is a kind of knowledge not to be obtained from books; it can only be gathered from patient and intelligent handling of the rocks themselves. In the field, the observer who has had this training in PETROGRAPHY, as the study of rocks is termed, can recognise most of the rocks he encounters. A pocket-knife, lens, and acid-bottle will assist him if his eye does not readily detect the characters of the stone. But it will often happen that he requires to subject a rock to more careful examination at home, before he can decide as to its nature and name; while, in other cases, he may require to call in the aid of an experienced petrographer.

It is absolutely necessary that the field-geologist should familiarise his eye with certain important minerals which enter largely into the composition of rocks, so as to be able to identify and distinguish them, and thereby the rocks which they constitute. For this purpose he should procure a collection of these minerals, and subject them to careful examination, so as to fix their characters in his mind; while at the same time he will not omit to devote as much time as he can spare to the attentive study of any good mineralogical cabinet within his reach. The number of minerals which form essential constituents of widely-diffused rocks is comparatively small. Nor are those very numerous which occur abundantly as important accessory or accidental ingredients. In Chapter XVI the reader will find a list of those which it is desirable that he should know, with a reference to the part they play as constituents of rocks.

But if the geologist means to devote himself to the study of the genesis of rocks, particularly those of igneous and metamorphic origin, he will find it needful to enter much more fully into the domain of MINERALOGY. Nor will he regret such an excursion; for in studying the structure and growth of minerals he learns how rocks have been formed, and by what processes they have been altered since their formation. This is well brought out by the microscopical examination of crystals, as will be pointed out in a later chapter.

Though practice alone can give the learner justifiable confidence among rocks in the field, some hints may be offered here for his guidance. He must learn to distinguish between essential and accidental characters. Two rocks for instance may exactly resemble each other in colour, and even in shade of colour, yet the one may be a derivative or sedimentary mass, the other an original or igneous one. Colour, therefore, can hardly be a very trustworthy index of the true nature of a rock (but see p. 68).

Again, a rock may at one place be so compact and tough as to be broken with difficulty, though at a short distance it may be as soft as loose gravel or sand. Wide variations in texture likewise occur; a mass of rock will here present a coarsely crystalline or almost granitoid aspect, while there it may be so close-grained as to appear nearly homogeneous.

In his field-work, therefore, the learner will discover by experience what are the essential characters in each case. Reserving more precise and detailed investigation for indoor work (see Chap. XVI), he will find that with the unaided eye and such instruments as can be carried in the field, he can take note of the following particulars of the rocks: 1. Fresh fracture and weathered surface. 2. Apparent structure and texture. 3. Hardness and streak. 4. Colour. 5. Smell. 6. Feel. 7. Behaviour in mass.

1. Fresh Fracture and Weathered Surface.—All rocks yield more or less to the corroding action of the atmosphere. Some, like pure limestone, are dissolved by rain, the dissolved material is carried away, and the surface of the rock may remain bare, clean, and hard. But most of them show a more or less distinct crust or outer crumbling skin, which is thicker or thinner, according to the resisting power of the rock on the one hand, and the vigour of the decomposing agents on the other. In this outer weathered crust we may often observe the composition of the rock better than on the fresh fracture. The very existence of such a crust

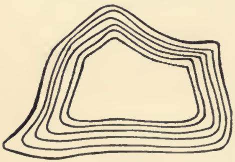


FIG. 5.—Weathered crust, showing concentric zones of oxidation.

depends upon unequal decay; some one or more ingredients of the rock disappear faster than the others which may remain isolated and comparatively little altered in the crumbling *débris* of the decomposed constituent. For example, in many close-grained and crystalline rocks, consisting of quartz and felspar, these two minerals are so intermingled and so resemble each other in colour and lustre, that at a first glance they might not

FIG. 5*a*.—Granite weathering along its joints. Top of Bennachie, Aberdeenshire.

be distinguished; but on a weathered surface their clearly defined differences stand out very sharply; the felspar acquires a dull earthy texture, while the more durable quartz projects in hard glassy grains. A large number of rocks are characterised each by its own type of weathering. Thus, granite is apt to split along its joints and to assume, as it decays, the aspect of ruined walls and buttresses of cyclopean masonry (Fig. 5*a*). Basalt-rocks are prone to develop a spheroidal structure, each globular mass exfoliating into concentric onion-like coats (Fig. 6). Limestone and dolomite project in bare, smooth, bleached

FIG. 6.—Dolerite (basalt) weathering spheroidally. North Queensferry.

knobs, curiously fretted, channelled, and honeycombed; the grass around is usually greener than elsewhere, and the ground is often perforated with swallow-holes, tunnels, and ramifying passages.

The contrast between a weathered and a fresh piece of the same rock is often so extreme that the beginner would not readily believe them to be from the same mass, unless he had himself detached them. Basalt, for instance, on a fresh unaltered fracture, is a compact or finely crystalline rock, heavy, and of an iron-black colour. But on a weathered cliff it may be seen of every hue from bright yellow to sombre brown, and in many places so soft as to be capable of being dug out with a spade. The beginner, therefore, should on no account omit to make himself acquainted both with the unaltered and the altered conditions of rocks. By degrees he will learn to recognise a rock through all its protean disguises of weathering, and distinguish it even at some distance.

2. Apparent Structure and Texture.—The nature of the component particles, and the manner in which they are arranged so as to build up the mass of the rock, constitute important characters. The geologist in the field has of course only very limited means of investigating these characters, so that when they become doubtful and obscure he may be compelled to defer the solution of his difficulties until he can find opportunity in-doors of subjecting the rocks to more detailed and careful scrutiny. But with the aid of his pocket-lens he may be able to recognise three types of structure among rocks which may be termed respectively Crystalline, Compact, and Fragmental. He can, therefore, in the field provisionally group the rocks which he encounters under one or other of these subdivisions until more detailed investigation has enabled him to determine their characters with greater precision.[1]

[1] It will be understood that this classification is intended only as a guide for the first identification of rocks *in the field.*

i. CRYSTALLINE.—In this type the rocks have a granular structure, and on inspection the apparent grains are found to be crystals, or crystalline particles, so intermingled, or felted together, as to give coherence to the stone. In the coarse-grained varieties, like many granites, the crystals of which can be distinctly seen at a distance of several yards, their true crystalline nature is at once apparent. We see that their grains are all crystalline, and that the lustre reflected from so many shining points on their surface comes from the cleavage planes of the component minerals. But as the texture becomes finer, as it does, for example, in the family of the basalt-rocks, the unassisted eye may hardly be able to detect any crystalline facettes, even on a fresh fracture. The lens, however, will often show that such rocks really consist of very small crystals. But the fineness of grain may reach such a point as to escape detection even by that means, and then the observer must call the rock a compact one. It may still be quite crystalline, however, when examined under the microscope, in the manner described in a later chapter. We are at present concerned only with those external characters which can be recognised by the observer in the field.

FIG. 7.—A piece of granite. Crystalline structure.

Viewed broadly the crystalline particles are found to be built up on two different plans. In the great majority of rocks they are (i) amorphously aggregated, that is, they have crystallised together promiscuously without any definite arrangement, so that the rock presents much the same texture no matter in what direction it may be broken;[1] in a remarkable series of rocks they are (ii) schistose or foliated, that is, disposed in more or less distinctly parallel folia or laminæ of crystalline minerals.

(1st) Amorphously aggregated.—Rocks of this kind are α, *Simple*, or β, *Compound*.

(α) *Simple*.—Composed essentially of one mineral, though now and then with accessory ingredients. The rocks of this sub-group are almost entirely of aqueous origin, that is, they have crystallised from solutions in water. Crystalline limestone, dolomite, gypsum, and rock-salt may be taken as illustrative examples. A few silicates occur in this form, as in hornblende-rock, but most of them belong rather to the foliated type.

(β) *Compound*.—Composed of two or more minerals in an infinite variety of proportions. Most of the rocks which constitute this very important series are what are usually called Igneous; that is, they have crystallised out of molten solutions like modern lava. They almost invariably consist of silicates of alumina, with magnesia, lime, potash, soda, and varying proportions of iron oxides,

[1] Closer scrutiny will sometimes show that the constituents of a rock are not so irregularly aggregated as might be supposed. In graphic granite, for instance, the quartz and felspar have crystallised with their longer axes parallel; in granophyre these minerals are intimately and regularly intergrown; in spherulitic rocks spherical grains or pea-like aggregates show an internal fibrous radiating structure, and sometimes run in rows. Many igneous rocks while in an unconsolidated condition have acquired what is called *flow-structure*, that is, their constituents have been drawn out in the direction of movement of the still uncongealed mass, see p. 172.

phosphate of lime, etc. The great majority of them are mainly composed of some felspar, or at least contain a large percentage of that mineral, with such silicates as hornblende, augite, olivine, biotite, and muscovite; free silica in the form of blebs or crystals of quartz; iron oxides, particularly magnetic and titaniferous; apatite, etc. Hence they are commonly distinguishable from the simple rocks by their greater hardness, toughness, and weight. Granite, syenite, quartz-porphyry, diabase, basalt, diorite, trachyte, are examples of compound rocks.

Many varieties of texture occur among these rocks. The following are among the more important: *Coarse*

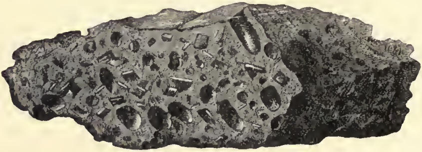


FIG. 8.—Piece of porphyritic and cellular lava (showing crystals and steam-holes).

crystalline; *fine-crystalline*; (*crypto-crystalline*, where the crystals are so minute as to appear only under the microscope, might be placed by the field-geologist in the compact series); *porphyritic*—having large crystals, usually of felspar, scattered through a compact base (Fig. 8); *cellular*—full of spherical cavities formed by the expansion of imprisoned steam during the outflow of the rock (Fig. 8); *scoriaceous*—roughly and irregularly vesicular, like the scoriæ of a lava stream, or the "clinkers" from a foundry; *amygdaloidal*—full of almond-shaped concretions of calcite, calcedony, zeolites, or other minerals;

the concretions having been deposited by infiltration in steam-holes of the rock, so that when they weather out, the original cellular aspect of the mass is restored.

(2d) Schistose.—Rocks of this group are distinguishable by the peculiar arrangement of their component minerals into parallel layers or folia. These layers consist sometimes mainly or wholly of one mineral, as in hornblende-schist; more usually they are composed of two or more minerals, as in mica-schist and gneiss. They may be observed to run into each other and to be as it were welded together. Yet they are distinctly crystalline. In many cases they present a wrinkled or crumpled aspect, showing that they have been puckered by strong lateral pressure.

ii. COMPACT. — Without recognisable component crystals or particles, so far as can be made out in the field, but with a close, homogeneous texture. Three leading varieties may be noticed — 1st, Glassy and resinous; 2d, Horny; 3d, Fine-grained.

(1st) Glassy and Resinous—resembling bottle-glass or pitch. This sub-group includes the natural glasses, as obsidian, pitchstone, and basalt-glass. Some hydrocarbons, as amber, asphalt and anthracite possess a marked resinous texture; but their specific gravity and behaviour when heated at once distinguish them from the volcanic glasses.

(2d) Horny—having a feebly lustrous, translucent character, like flint. The chalk-flints and the cherts of older formations are good examples, and the same texture is often exhibited by devitrified volcanic rocks such as some rhyolites and felsites.

(3d) Fine-grained—having a dull, exceedingly close granular texture, which may pass into the fine varieties of the crystalline amorphous rocks on the one hand, and of the fragmental rocks on the other. Many limestones and felsites show this texture.

As some of these textures characterise rocks of very different geological structure and origin, they evidently must be used with caution as a means of identification. When there is room for doubt, other characters should be looked for, and final appeal may have to be made to the microscope. But cases will from time to time arise when even with the help of that instrument no satisfactory opinion can be formed as to the nature of a rock. Especially is this true where the stone has undergone some degree of decomposition.

iii. FRAGMENTAL (*Clastic*)—composed of fragments of

FIG. 9.—Piece of conglomerate, showing the characteristic rounded water-worn aspect of the component parts of many fragmental rocks.

pre-existing rocks or minerals. As rocks of this type are mere mechanical mixtures, they present an endless variety, both in composition and texture. In the vast majority of cases they are of aqueous origin, that is, they have been laid down as sediment in water. Their component pebbles and grains are therefore usually more or less rounded and water-worn (Fig. 9). But minute crystalline particles derived from older rocks are apt to retain their angularity, as fine sand does which, swept along in suspension by a river, undergoes no attrition on the way. The coarse varieties, consisting of compacted gravel, are termed *conglomerates* when formed of rounded, *breccias* when formed of angular fragments. These

FIG. 10.—Piece of volcanic tuff.

coarse-grained rocks pass into *grits* and *sandstones*, where the materials, usually more or less siliceous, have been reduced to the condition of sand. Sandstones are in the majority of cases composed of grains of quartz, which are often well rounded, and when examined with a strong lens or a microscope look like large rounded boulders. *Argillaceous* rocks are those composed of the muddy or clayey sediment, sometimes arranged in laminæ of deposit, as in *shale*, at other times with no fissility, as in *fireclay* and *mudstone*. An important series of fragmental rocks has been formed by the consolidation of the loose dust and blocks ejected by a volcano. To these the general term *Tuffs* has been applied (Fig. 10).

With the fragmental rocks may be classed those which have been formed of the fragmentary remains of plants (Fig. 11) and animals. Ordinary crinoidal limestone (Fig. 15) is a characteristic example, consisting as it does

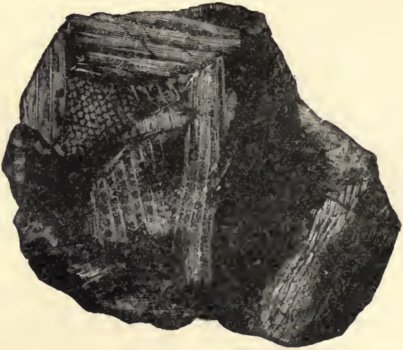


FIG. 11.—Piece of coal, composed of matted stems of *Sigillaria* and *Lepidodendron*. Carmarthenshire. (De la Beche.)

of the congregated joints and plates of encrinites, with more or less perfect mollusca, corals, echini, fish-teeth, etc. Some of these organically-derived rocks, however, possess textures which would justify their being called compact rocks, as in the case of cannel coal. Others again, have acquired, in large measure, a crystalline texture, as has happened so abundantly in the Mountain Limestone. The reader is referred to Chapters XVI and XVII for further information on this subject.

3. **Hardness and Streak.**—Rocks differ much from each other in hardness; even in the same mass of rock considerable diversities in this respect may be met with. Hardness is a character of secondary importance, though it may often be usefully employed to distinguish, among the compact rocks, siliceous from softer calcareous masses. Obviously it can only be properly applied to perfectly fresh surfaces, and is suited to homogeneous rather than to compound rocks. For the purpose of applying it in the field, a pocket-knife should be carried, but if the hammer has sharp corners on its cutting edge, these if drawn across the surface of the rock will serve the purpose. The scale of hardness employed in mineralogy may be used in testing rocks. This subject is further referred to in Chapter XVI.

Streak is the name given to the powder made when the knife (or file, or diamond) is drawn across the surface of a mineral or rock. Though sometimes useful in mineralogy it is not often of much service among rocks. It may now and then be employed to distinguish compact dark bituminous clays or shales from varieties of coal, the former giving a dull brown or grey powder, and the latter a lustrous black streak. In the case of impure calcareous rocks, when little or no effervescence is visible in a drop of weak acid placed upon the clean surface, brisk disengagement of carbonic acid may often be produced by dropping the acid over the powder made by a scratch with the knife. Of course, individual minerals which occur either as original or accidental constituents of rocks may be tried for streak in the usual way required in mineralogical inquiry. Small specks of hæmatite may thus be detected by their characteristic cherry-red streak, while the iron-peroxide when hydrated (limonite) will show its brown or yellow streak.

4. **Colour.**—Great caution must be exercised in making use of this character in the discrimination of rocks. The same rock may, even within short distances, display the most extraordinary varieties of colour. But within certain limits the colour of a rock is an indication of the nature of some at least of its constituents. Iron is the great pigment to which the rocks owe their diversities of hue. It gives rise to numerous tints of yellow, brown, red, and green, as well as to blue and black. Some hints as to the causes of a few common varieties of colour may be of service.

White.—Limestones and clays are often quite white, and in this condition are almost always at their purest. Iron is generally absent, or present in but small quantity, in white rocks. The result of weathering is often to bleach rocks white, the air and rain removing the colouring materials, more especially the iron. The stones in a morass, or below peat are commonly bleached on the outside as white as chalk—the result of the reducing action of organic acids from the peat on the iron oxides, which are removed in solution or suspension, as organic compounds or as carbonates.

Black.—Many carbonaceous rocks are black. Coals may be distinguished by their lightness, texture, and combustion. Clays or shales, rendered black by the vegetable matter they contain, may be recognised by their weight, streak, and their turning white but retaining their shape when strongly heated. But black heavy rocks abound in which there is no trace of carbon. These very generally contain a considerable amount of iron, either in the form of magnetite, ilmenite, or other related oxide, or in that of some black ferruginous mineral, such as hornblende. Such rocks are apt to weather with a brown or yellow crust, owing to the conversion of the iron into the hydrous peroxide.

Brown.—This colour characterises some rocks on their fresh fractures, as the variety of ironstone called blackband. A few crystalline rocks have a brown tint from the presence of minerals of that colour, such as varieties of mica and garnet. But it is more particularly on the decomposed surfaces and crusts of rocks that brown tints appear. The iron is there converted into the hydrous peroxide (hydrated ferric oxide, limonite). Basalt-rocks show this change in a most instructive manner. Earthy manganese also gives dark brown to black tints.

Yellow.—The colouring material of yellow rocks is almost always limonite. Yellow sandstones, beds of ochre, the weathered crusts of many limestones and of numerous ferruginous crystalline rocks furnish illustrations. Sometimes a metallic or brassy yellow is communicated to parts of rocks by diffused iron-pyrites; when this yellow is of the pale kind due to marcasite, it can only be seen on fresh fractures, as it disappears with the rapid decomposition of the mineral.

Red.—The prevailing hue of red rocks varies from a brownish-red to a bright brick-red, and is due to the presence of the anhydrous peroxide of iron (ferric oxide, hæmatite). Such rocks are often mottled with or pass into yellow and brown tints, where the iron they contain has been hydrated. These colours are most typically displayed among red sandstones and clays, of which an enormous mass occurs in the Old Red and New Red Sandstone, and in the Permian series. Some rocks show a delicate flesh-red tint from the colour of their orthoclase felspar, as in pink granite. Iron is in this case also the pigment.

Green.—Many red sandstones are marked with circular spots of green, due to the reduction of the iron-oxide. Protosilicate of iron is the prevalent green pigment of rocks; carbonates of copper sometimes colour rocks of bright verdigris and emerald-green tints. Many magnesian silicates are green, and impart green colours of various hues to the rocks of which they are constituents. Thus hornblende and augite give rise to dark bottle-green, and among the schistose rocks to paler apple-green and leek-green tints. Epidote diffused abundantly through a rock gives it a yellowish or grass-green hue. The hydrous magnesian silicates, talc, chlorite, and serpentine, form characteristically green rocks, the talc rocks shading off through leek-green or apple-green into white, and serpentine into black and dark red. Glauconite extensively diffused through certain sandstones gives them a characteristic green colour, as in the well-known Green Sand.

Blue is not a frequent colour in rock masses. It is often spoken of as the colour of many limestones, which, however, are grey or bluish-grey. Beautiful belts of pale blue and white occur among the schistose rocks where the mineral kyanite abounds. Some clays and lithomarges are of a pale lavender-blue. Patches of a bright smalt blue, or of an indigo tint, may be met with among peat-mosses, where some animal organism has decayed and given rise to the formation of phosphate of iron (vivianite).

Grey may be said to be the prevailing colour among rocks, especially of the older geological periods. In simple rocks like limestones it is often produced by the intermingling of minute particles of clay, sand, or iron-oxide, or of amorphous carbonate of lime with the paler crystalline calcite of the comminuted organisms. Pure crystalline limestone is naturally snow-white, as in Carrara marble. In compound rocks the prevailing grey hues depend on the mixture of a white mineral, usually a felspar, with one or more dark minerals like magnetite, hornblende, or augite, the lightness or darkness of the hue depending upon the relative proportions of the constituents. Should the felspar be coloured by iron, a pinkish hue may be given to the grey; or if the dark magnesian silicates have been altered into some of their hydrous representatives, the grey becomes more or less distinctly green. The old "greenstones" probably originally grey, often owe their present distinctive hue to an alteration of their original minerals, and especially to the development of chlorite or epidote in them.

5. Smell.—Clay-rocks may be recognised by the peculiar earthy (argillaceous) odour they give out when

Fig. 12.—Outlines of mountains formed of stratified or sedimentary rocks. Rocky Mountains. (*Hayden's Report of Survey of Western Territories, 1874.*)

breathed upon. Crystalline felspar rocks when breathed upon often yield this smell. Some rocks, especially limestones containing animal matter or decomposing iron-sulphides, yield a fetid or rotten-egg odour when freshly broken.

6. Feel. — A few rocks are characterised by a peculiar feeling to the touch. This is chiefly shown by the hydrous magnesian silicates, talc, chlorite, serpentine, etc. (also by some micaceous schists), which have a greasy or soapy feel. In large tracts of country formed of chlorite-schist, margarodite-schist, or serpentine rock, the stones have everywhere this characteristic. The term "trachyte" was originally applied to certain volcanic rocks distinguished by the harsh, prickly feeling experienced when the finger is passed over their surface. A rock like chalk is said to be *meagre* to the touch.

7. Behaviour in Mass. — There are some remarkably characteristic aspects of rocks which cannot be judged of in hand specimens, any more than the architecture of a building can be told from the nature of the stone employed in its construction. It is as parts of the architecture of the earth's crust that rocks present many of their most typical and individual features. These broader and larger characters show themselves in the outline of every hill and mountain. As illustrations we may take the two contrasted groups of the stratified fragmental and amorphous crystalline rocks. Even from a distance the difference between these rocks makes itself felt in the striking distinctions so often visible in the form of mountains. Thus in Fig. 12 it will be noticed that two prominent sets of lines can be traced all

Fig. 13.—Outlines of a mountain formed of crystalline rock. Rocky Mountains. (*Hayden's Report for 1874.*)

along the crests and declivities—the horizontal lines of the bedding and the vertical lines of the joints. The rocks are cut into huge blocks in the process of denudation, and these blocks are further channelled and chiselled along the dominant divisional lines. With this rectilinear style of architecture compare that of a mass of granite, one of the amorphous crystalline rocks (Fig. 13). No parallel systems of lines here catch the eye. The crests are splintered, indeed, along the joints, and these divisional lines may be traced by a practised eye down many of the cliffs and steep declivities of granite, but they never show the definiteness, regularity, and alternation of prominent and retiring bands so typical of stratified rocks. The general lines of the mountain are graceful curves rising more and more towards the summits till they often become vertical.[1]

The stratified rocks, then, are distinguished by their arrangement into beds, varying according to the nature of the substance, from the finest laminæ up to large masses many yards in thickness. The amorphous crystalline rocks, on the other hand, are marked by the absence of all structure except their joints. The reader will find this subject further illustrated in succeeding chapters; but he will learn more by a little practice in the field than can be easily communicated by books.

[1] The geological sketches of Mr. W. V. Holmes in the publications of the United States Geological Surveys, and those of Dr. A. Heim in his book on the Mechanism of Mountain-building, and in the Beiträge of the Swiss Geological Commission, may be profitably studied by the geological observer as models of artistic and scientific delineation.

CHAPTER VII

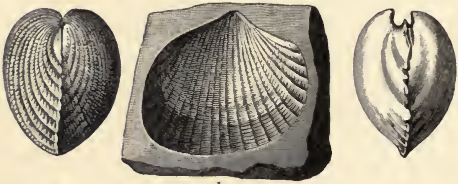
THE NATURE AND USE OF FOSSILS

In probably the great majority of cases, it is the interest attaching to the remains of once living plants and animals imbedded in the rocks which induces people to read geological books and to devote their time to the endeavour to gain some practical acquaintance with geology. But as a rule the practical work begins and ends with the gathering of the specimens. In the present chapter I wish to show that apart from their interest or beauty as specimens which can be arranged in a collection, the relics of former organisms are of the utmost value in geological inquiry,—that in fact, so far as relates to the chronological succession of geological history, their importance is paramount.

A "fossil" is literally anything dug up. The word, formerly applied indiscriminately to any mineral substance taken out of the earth, whether possessing organised structure or not, is now restricted to the remains or traces of plants and animals which have been imbedded by natural causes in any geological formation, whether ancient rock or modern superficial deposit. Thus under the designation "fossil" we must include the entire carcases of mammoths and rhinoceroses which have been preserved for ages with their flesh and hair, frozen up in some of the muddy soils of Siberia; the skeleton of a stag preserved in a peat-bog; the scales and teeth of fishes scattered through a solid limestone; the shells of mollusca, the calcareous framework of corals, the compressed leaves, fruits, and stems of plants; in short, any and every part of an organism which has been imbedded in a geological formation, no matter what may be its condition of preservation, and whether or not it has been partially or wholly petrified.

But not merely must we include every portion of the organism; we may properly class also with fossils every substance or marking which has been connected in any way with the organism and bears witness as to its existence and character. Thus, the resin of a tree, the trail or the castings of a worm, the droppings of animals, even the tools and weapons of man, may all become fossils and yield their evidence as to former conditions of life.

As the circumstances under which fossils have been entombed have greatly varied, the observer must be prepared for the most extraordinary differences in the appearance of even the same species of fossil in different places and kinds of rock. In some rare examples the body of an animal has been so entirely and perfectly preserved that, as is said to have been the case with the Siberian mammoth just referred to, its flesh may be torn in pieces and devoured by beasts and birds of prey. As a rule, however, the soft parts of the organism are gone. Where there have been harder parts, such as an internal skeleton or an external covering, these may still remain nearly or quite in their original condition. As a rule, however, even the harder parts have undergone some change; they have lost some portions of their original substance, more particularly the animal matter, and have had mineral material infiltrated instead. And the process of replacement has often continued until the whole of the original bone or shell or stem has been removed and has been at the same time replaced, particle for particle, by carbonate of lime, silica,



a *b* *c*

FIG. 14.—Common Cockle (*Cardium edule*); (*a*) side view of both valves; (*b*) mould of the external form of one valve taken in plaster of Paris; (*c*) side view of cast in plaster of Paris of interior of the united valves.

spathic iron, or some other mineral substance, whereby the minute structure of the organism has been more or less perfectly, sometimes indeed exquisitely, preserved. In other cases, the whole of the material of the animal or plant has disappeared, and has been replaced by a cast which retains the external form of the original, but is internally entirely structureless; or the cast, if there ever was one, has been destroyed, and only an empty cavity remains to mark where the organism once lay. In the case of the mollusca we may have a cast of either the external or internal form of the shell. The observer will often be puzzled at first by such internal casts, as he will at once understand if he takes the two valves of an empty cockle-shell, places them in their original position, and, after making a small hole in one of them, pours in liquid plaster of Paris until the internal cavity is filled with it. When the plaster has set he can remove the valves, and he will have an internal cast of the cockle. But had he seen the object before making the experiment, he would not have been likely to guess what it was (Fig. 14).

Again, at the outset he may experience some difficulty in identifying the same fossil when it occurs in different kinds of stone. For example, a plant which, when preserved in shale or any argillaceous layer, may retain each leaflet, scar, and surface-marking, will perhaps appear in sandstone as a mere black streak of coaly substance. A fossil fish, which if found in a limestone nodule may have every scale and bone in place, each with its peculiar sculpture delicately shown, may, if met with in a conglomerate, occur merely in scattered fragments, all so much rounded and worn as to be hardly recognisable.

A little experience will guide the learner to those rocks which are likely to contain fossils. No general rule can be laid down; for the kinds of rock which are barren of organic remains in some places, abound with them in others. Conglomerates, for example, are not usually rocks in which we should expect to meet with fossils; nor as a rule do we find them there. Yet there are many richly fossiliferous conglomerates, such as those of the Silurian rocks of Penwhapple Glen in Ayrshire, and of the Upper Old Red Sandstone in several parts of Scotland. Argillaceous rocks are commonly better grounds for fossil-hunting than sandstones, and limestones are better than either. The shaly bands, however, which lie above a limestone are often more prolific than the limestone itself, as the fossils can be extracted entire from the soft, surrounding matrix.

The inspection of a well-arranged series of fossils in a museum, all cleaned and neatly labelled, affords but small assistance in the practical work of finding the fossils in the rocks. The learner must betake himself to the localities from which he knows that fossils have already been obtained; or if it is a district not yet explored for fossils, he must carefully note first of all the characters of the rocks. He will discover after some practice that it is not luck, but skill and good eyesight, which make the successful collector. Two observers may go over the same ground; one of them diligently applies his hammer, breaks up innumerable blocks of limestone, finds not a single recognisable trace of a fossil, and pronouncing the rock to be unfossiliferous, passes on; the other, perceiving the calcareous nature of the stone, and therefore its possibly fossiliferous character, puts his hammer in his belt, and betakes himself at once to the *weathered blocks*. He knows, as every one soon does who attends to the subject, that in many cases a rock, which is really highly fossiliferous, may not appear to be so on a fresh fracture, where the whole texture of the stone may be uniformly crystalline. But when exposed to the slow corrosive influence of the weather, the difference between the molecular arrangement of the calcareous matter in the organic remains and of that in the surrounding matrix begins to appear. Shells, corals, and crinoids stand out in relief on the weathered stone, showing even some of their most delicate sculpturing, while the surrounding limestone has been slowly dissolved and removed (Fig. 15). In other cases the material of the organisms has been less durable than that of the surrounding matrix, and mere moulds of the fossils are preserved. By pressing wax

FIG. 15.—Fossils standing in relief on a weathered surface of limestone.

or heated gutta percha into these moulds, casts may be obtained. In this way a rock which may have been supposed to be unfossiliferous by one observer is shown by another of greater training to be full of fossils. Old walls and buildings, the refuse heaps of old quarries, the angular blocks strewn at the base of a cliff—in short, all surfaces of rock which have been lying exposed for a long while to the gentle influences of the air, rain, and frosts, may be made to yield their evidence as to the fossils in the rocks of a district.

Apart from the interest of fossils in relation to the evolution of life, there are five important purposes to which the geologist can apply them: 1st, to throw light upon revolutions in climate; 2nd, to restore former conditions of geography; 3rd, to detect former movements in the crust of the earth; 4th, to afford horizons which serve to unravel geological structure; and 5th, to fix the relative geological date of rocks.

1. *Climate.*—Within certain limits, fossils may be employed to show under what conditions of climate the geological formations of bygone ages were accumulated. We know, for example, that in the older Tertiary periods in Europe the temperature must have been considerably higher than it is now, for in strata of that age we find among the fossil plants, forms of palm, custard-apple, laurel, fig, and numerous conifers; together with remains of turtles, crocodiles, sea-snakes, tapir-like pachyderms, and many mollusca belonging to genera now living in warmer seas than those of Western and North-Western Europe. On the other hand, it can be shown that the general climate of Central and Northern Europe at a later time became quite arctic in character, for the remains of the reindeer and the musk-ox occur in superficial formations even far south in France; bones of the arctic lemming, mammoth, woolly rhinoceros, and other northern mammalia, mark the cave-deposits and other surface accumulations in the South of England; shells now extinct in our littoral waters, but still living in those of northern seas, abound in the clays which fringe the coasts of the West of Scotland.

It must be borne in mind, however, that the argument from organic remains may be pushed too far. When we are dealing with species no longer living, we need an accumulation of evidence to warrant any deduction from them as to climate. Two species of the same genus may flourish under very different conditions of climate, as we may see from the fact that the *Elephas primigenius* or mammoth was a thick-furred northern form, though his modern representatives inhabit intertropical latitudes. Hence it is not by one species, but by the whole assem-

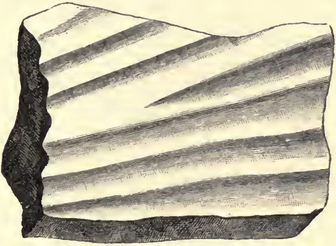


FIG. 16.—Ripple marks in sandstone.

blage of the plants and animals, or what is called the fossil flora and fauna, of a formation, that the climate in which the organisms lived must be judged. The further removed the fossils are from us in time, the more do they differ from living forms, and the less reliable are they as witnesses to climate.

2. *Geographical Conditions.*—In most cases it is only from the character of the included organic remains that the conditions under which stratified deposits were laid down can be determined. By the evidence of fossils we

may confidently identify former land-surfaces, lake-floors, and sea-bottoms. (1) Land-surfaces are revealed to us by layers of terrestrial vegetation resting upon what must once have been soil and still contains the roots of the plants that grew upon it. Stumps of trees in their position of growth, with, it may be, their fruits and leaves lying around, and even an occasional wing-case of a beetle, or the remains of a lizard or land-snail, furnish unimpeachable proof that the localities where they occur were once tree-covered tracts of ground. Hence the

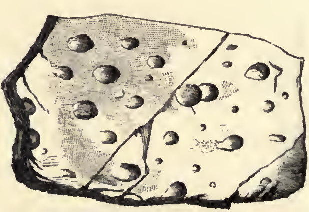


FIG. 17.—Rain-prints on sandstone.

occurrence of such a terrestrial layer in a group of strata proves that during their deposition a pause ensued, and their site became land. Traces of ancient shores, or at least of shallow water, are often preserved in ripple-marked surfaces of sandstones (Fig. 16) on which the trails or burrows of annelides may now and then be observed. If rain-prints (Fig. 17) are associated with rippled surfaces, they conclusively prove the sediment to have accumulated on a shore. Further evidence of the occasional exposure of the deposits to air and sun is yielded by the desiccation-cracks so commonly found among sandstones

(Fig. 18); while now and then, footprints of birds and different quadrupeds, impressed on the soft sand, com-

FIG. 18.—Sun-cracked surface of red sandstone marked with footprints. Hildburghausen, Saxony.

plete the picture of quiet shore-conditions of deposit. (2) Lacustrine shells and cyprid cases point to former lakes. A layer of white marl full of decaying forms of

Limnea, *Planorbis*, etc., may often be found below the grassy surface of a flat meadow. Such a layer as certainly demonstrates that the meadow was once a lake, as if we had documentary evidence to prove that such had been the condition of the place within the last few generations. (3) Corals and other zoophytes, mollusca of such genera as *Lingula*, *Cyprina*, *Buccinum*, and *Rissoa*, likewise fishes of such types as the ray and shark, point to marine conditions of life. The conclusion that any particular stratum must have been laid down on the sea-floor might not be warranted were it made to rest on merely a single fossil. Shells and crustacea, for instance, are often carried inland by sea-birds, and their remains may be left there to be covered up together with those of terrestrial animals. But when the whole character or *facies* of the fossils of a rock is of a marine type, we may confidently infer that the rock was deposited on the bed of the sea. Certain forms of life have had a remarkable persistence in the ocean. Some of the living brachiopods, for example, are closely similar to those even of very early geological periods. These persistent forms, though they do not absolutely prove, yet give strong grounds for believing that, as they are all marine forms now, so they must have been marine from the beginning. And when they are found associated with other forms belonging to recognisable marine types, the inference cannot be resisted.

3. *Terrestrial Movements.*—The importance of organic remains as witnesses of movements of the earth's crust depends upon the limitation of organisms to their own conditions of existence. A group of living sea-shells cannot be found in an inland lake, nor will a

living terrestrial vegetation be dredged up from the sea-floor.[1] If, therefore, marine forms of life must be taken as evidence of the presence of the sea and terrestrial forms as proofs of land, these furnish us with an easily applicable and reliable test of change of level between sea and land, as well as a measure of its minimum amount. A natural terrace of sand and gravel, full of littoral shells,

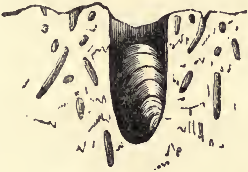


FIG. 19.—Limestone bored by lithodomous shells.

and extending along a coast-line at a height of 100 feet above the present sea-level, shows that sea and land have shifted relatively to each other to the extent of at least 100 feet. Geologists are not all agreed as to whether in such changes of level it is the land or the sea which moves up or down. Where evidence can be obtained of marked local variations in the amount of change it is

[1] Exceptional instances may of course occur where close to the margin of the land fresh-water lakes may be entered by the sea, and there may be a partial commingling of marine and fresh-water organisms. But such examples will seldom lead to any mistake. For an interesting account of one illustration of this mixture of the life of fresh and salt water, see Hugh Miller's *Footprints of the Creator*, chap. i. Again, where portions of the sea have been isolated and carried upward on an upraised surface of land, so as to become inland lakes, marine types of life may in the course of ages survive and undergo modification as denizens of fresh water. The fauna of some of the African lakes may be cited in illustration.

inferred that they indicate movements of the land. The terrace or *raised-beach*, as it is called, is then said to mark an upheaval of the coast to the extent of 100 feet. Barnacles adhering to rocks, and living shells which have perforated them (Fig. 19) furnish similar proof of a change of level and probably, in the great majority of

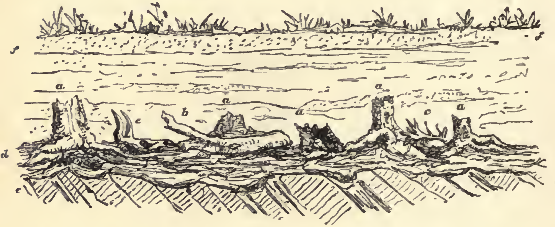


FIG. 20.—Section of a buried land-surface (De la Beche). *ee*, rocks underneath; *dd*, old vegetable soil; *aa*, stumps of trees still erect in position of growth; *b*, prostrate tree-trunk; *cc*, horns of oxen and deer. The whole buried under silt and modern soil, *f*.

cases, point to an actual elevation of the land. On the other hand, a submergence may be demonstrated to have taken place when a terrestrial surface, with its tree-stumps *in situ*, old soil and sylvan leaf mould, is found below high-water mark. The trees must have grown above the limit of ordinary tidal action, so that the amount of depression must always more or less exceed the vertical distance between the line of the submerged trees and the upper edge of the beach. Here again the same difference of opinion exists as to whether the apparent subsidence has been caused by an actual sinking of the land or a rise of the sea. Both causes no doubt from time to time come into operation. The observer should, however, be on his guard against the possibility that the submergence of tree-roots may sometimes not prove either subsidence of land or rise of sea, or any change of level at all. Where, for instance, an inlet or creek has been separated from the sea by a barrier of sand or other detritus, land plants and even trees may grow below the level of high-water. If the barrier is cut down so as to admit the sea, the tides will rise over submerged terrestrial vegetation, while all the time the relative levels of sea and land may have remained unchanged.

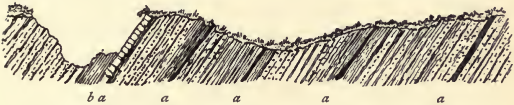


FIG. 21.—Section of inclined Carboniferous rocks, Joppa Quarry near Edinburgh, *a a*, coal seams; *b*, limestone with marine organisms. The dotted bands are sandstones, the shaded are shales and clays.

Among the geological formations which form the visible part of the earth's crust, it is sometimes possible to obtain instructive sections wherein successive terrestrial movements and conditions of physical geography are well illustrated. A good example occurs in Joppa Quarry, near Edinburgh. It will be seen from the accompanying section (Fig. 21) that five seams of coal occur, each representing a terrestrial surface, or at least an aquatic floor whereon grew a vegetation with its roots in the water and its branches in the air. There must have been a progressive subsidence until the first formed coal-seam had been buried under many feet of sand and mud which inclosed also the remains of other similar terrestrial surfaces. At last, by a more prolonged submergence and the clearing of the water, marine forms of life, zoophytes, encrinites, and molluscs, made their way into the area, and flourished so long as to form a bed of limestone about three feet thick. Subsequently the sediment returned, and as the water was filled up, new coal-growths sprang up as before.

The observer will find it sometimes possible, by means of fossil evidence, to prove that strata, apparently in their natural order, have really been turned upside down, so that what seems the top of each stratum is really the bottom. This could be shown if we found in one of these strata, a row of fossils in their positions of growth, but with their lower ends uppermost. Suppose, for example, that one stratum contained many erect stems of trees, and that in every case the roots of these stems branched out freely at the upper end into an overlying stratum, evidently an old soil. We could not, in such a case, come to any other conclusion than that the whole of the rocks had been overturned. Again, instead of a series of land-plants, imagine a number of bunches of coral, with their roots still in the position of growth but turned up to the sky. We could only explain that position by admitting that the rocks must have been inverted.

4. *Geological Horizons.*—Fossils have often a high importance in affording to the geologist a clue in his endeavour to unravel the geological structure of a region. He may discover, for example, that some particular stratum, marked by the occurrence in it of certain fossils, can be recognised and traced over a considerable breadth

of ground. He follows this stratum, using it as a datum-line from which to work out the arrangement of the series both above and below it. And in regions where the strata have been so greatly disturbed and dislocated that their structure could not otherwise be disentangled, a clue is often supplied by the occurrence of such fossiliferous zones. This use of fossils will be more evident when we come to deal in a later chapter with the tracing of geological boundaries, and the working out of geological structure.

5. *Geological Chronology.*—To fix the relative geological position of rocks, and thus to establish a succession or chronology, is doubtless the most important service which fossils render to geology. Mere resemblances or differences in the mineral character of strata are seldom good for great distances. We cannot always be sure, simply on the ground of general petrographical resemblance, that a group of strata on one side of a country is identical with a similar set on the opposite side. If they closely resembled each other in that respect, but contained totally distinct fossils, we should generally conclude, in spite of their outward similarity, that they could not be identified with each other, but must belong to different periods of geological time.

Each great stratified formation of the earth's crust is distinguished by its own characteristic fossils. A method is thus obtainable of recognising the relative geological date of fossiliferous rocks. To determine and name fossils is the task of the palæontologist. As a rule the field-geologist can do this only to a limited extent, though the greater his power in this respect the more valuable his services in the field. Part of his training should consist in the study of as good a series of typical fossils as he can consult. He ought to familiarise his eye with the leading genera and more characteristic species of each geological system and formation. Knowledge of this kind, so portable when carried in the head ready for use, so bulky and difficult to transport and use when contained in many learned volumes, enables him to decide for himself as to the geological horizon of the formations. Should he be in doubt about the determination of his fossils, he must submit them to an expert in the subject.

For many purposes of field-geology it is not absolutely necessary, though it may be very desirable, that we should know the names and the zoological or botanical grade of the fossils. What we need to know in the field is that certain organic remains, whatever be their nature or names, occur in particular beds of rock. We should be able to recognise them and use them as indices to mark out the strata, and thus to fix our geological horizon. William Smith, by whom this stratigraphical use of fossils was originally taught, knew little of the nomenclature or natural history of the fossils he dealt with. But he learnt to recognise them, and to judge accurately of their position in the geological series, and he made as admirable use of them in tracing the outlines of the development of the Secondary rocks across England as if he had been able to name and describe each species. Geology has made vast strides since his time. Though the field-geologist may use the fossils without any scientific knowledge of them, the sooner he obtains that knowledge the better for his work. The broad outlines of William Smith's days have to be filled in by more minute and exhaustive work now.

In fine, the field-geologist will find in all quarters of the world that an acquaintance with fossils can be turned to profitable account. It enables him at the outset to fix more or less definitely the relative age of the rocks among which he is engaged, and thus affords means of comparison with the corresponding rocks of other countries. Where his labours are of no ambitious kind, but where he works for the quiet pleasure and open-air life of the pursuit, the study of organic remains affords him an endless fund for delightful meditation. It shows him at one place evidence of an old sea-bottom, in the strata where marine remains are crowded together. At another locality it brings before him, in fresh-water shells and other forms, the traces of long-vanished lakes and rivers. At a third spot it reveals, in successive layers of compressed vegetation and hardened loam, the gradual depression and submergence of old forest-covered lands. In such cases, fossils suggest the lines along which his further search should be prosecuted for additional corroborative testimony as to the ancient aspects of the district in which he is at work. The land-plants, for example, lead him to look for fresh-water forms of life, for sun-cracked and rain-pitted surfaces of rock; while the occurrence of marine forms of life prompts him to search for other proofs of the ancient dominion of the sea.

CHAPTER VIII

THE TRACING OF GEOLOGICAL BOUNDARY-LINES

WHETHER or not the observer sets about the construction of a map, he can form but a limited notion of the geology of a country if he confines his attention merely to a few quarries or lines of natural section. Having learned in such openings what is the nature and order of succession of the rocks, he ought to try to follow them thence into other parts of the country, and in so doing, endeavour to note as he goes any variation in character which they may present, and to take account of every topographical feature which may serve to indicate the disposition of the rocks below.

A very short experience of geological work in the field suffices to show the observer that over wide spaces he cannot actually see what rock lies beneath him. He may get an admirable section laid bare in some ravine or brook, or by the shore of the sea; but beyond the limits of this section the ground may be deeply buried under vegetation, soil, sand, gravel, clay, or other superficial formation, and no other section may occur for an interval of, it may be, several miles. Yet he must form some conclusion as to the nature of the rocks between these places.

In cases of this kind, information may often be obtained from an examination of the soil. What we call vegetable soil is merely the upper stratum of decayed rock mixed with vegetable and animal remains (Fig. 22). It commonly betrays its origin by the still undecomposed fragments of stone mixed through its mass. In one tract, for instance, we may find it full of pieces of sandstone, to the exclusion perhaps of every other kind

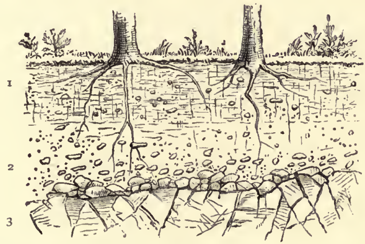


FIG. 22.—Section to show the superficial covering of soil (1); subsoil (2) derived from the disintegration of the underlying rock (3).

of rock. If the land has been under cultivation, the sandstone may be in large pieces, where it has been turned up by the plough. We should there infer with some confidence that sandstone lay *in situ* below. If again the soil were a stiff red loam, with few or no stones, it would indicate the existence of some red marl or clay immediately beneath. A sandy soil full of well-rounded, water-worn stones, would show the presence of some underlying gravelly deposit. A calcareous soil full of blocks of flint would probably indicate the existence of chalk. A stiff argillaceous soil, abounding in smoothed stones, many of them well-striated, would prove that a boulder-clay or till lay below. A profusion of fragments of some peculiar rock, a basalt, for example, or a diorite, or a porphyrite, extending in a definite band across a field or hillside, would probably show us that a rock of that character existed, *in situ*, somewhere in the immediate neighbourhood of the fragments. We require, of course, in all these cases, to go carefully over the ground, and draw our conclusion only after we have exhausted all the evidence procurable.

But it may be remarked that, except on freshly-ploughed land, the soil is not bare and exposed to our scrutiny; that, on the contrary, it is commonly just as much concealed by its coating of vegetation as the hard rocks are by their covering of soil. Even under the most unfavourable circumstances, however, the geologist may glean not a little of the information which he needs. Where the ground slopes, he will probably have no great trouble in finding some little rut or trench which has been cut, or at least deepened, by rain, and where he will obtain access to the underlying soil, or even, it may be, to the subsoil and the still undecomposed rock below it. Where, on the other hand, the ground is too flat to hope for assistance from rain-action, he will look for traces of burrowing animals, by which the soil may have been thrown up to the surface. In Britain, the common earth-worm, the mole, and the rabbit, are excellent coadjutors in his work. The fine castings of the earthworm give him at least the colour and general constitution of the soil, whether sandy or clayey. The heaps of the mole include the smaller stones in the soil, and permit an inference to be drawn as to the probable nature of the materials from the decomposition of which the soil has been formed. The extensive excavations of the rabbit lay bare not only the constitution of the soil, but often also the angular *débris* which rests immediately upon the solid rock.

From vegetation, also, the field-geologist learns to draw many a shrewd inference as to the character of the soil and rock below. A spring, or line of springs, indicative of some geological boundary-line, such as the

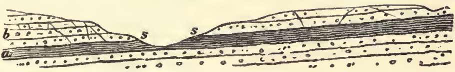


Fig. 23.—Section of a valley showing the outcrop of a junction of sandstone and shale marked by a line of springs, *s*, *s*.

junction of a harder or softer stratum (Fig. 23), or a line of fracture (Fig. 37), will reveal itself by marshy ground or by a brighter green along a hill slope. The course of a limestone band or a basalt-dyke may be followed, by the peculiar verdure of its vegetable covering, across a moorland where little or no solid rock may be seen. A ridge of serpentine stands up bare and rough, affording at best but an unkindly soil for plant-growth. Trees, too, change with the varying character of the rocks or soils on which they grow. Each country presents its own illustrations of these relations, which must be gradually learnt and made to give their assistance to the observer's progress.

In judging of the probable character of the rocks underneath from the nature of the overlying soil, the geologist will, of course, be guided by the local circumstances of each case. For example, if the surface of the ground should present many rounded pebbles and boulders, he will not at once conclude that these fragments have been derived from solid rock below. Their rounded forms will rather raise a suspicion that they have been transported, and should many of them plainly show the characteristic smoothed surface of water-worn stones, they will be set down as derived immediately from some adjacent bed of gravel or conglomerate. The mere fact of a great variety of separate rounded rock-fragments occurring over the surface at any locality, suggests a mass of transported material, rather than the decomposition of the solid rock underneath.

On the other hand, the occurrence of abundant angular fragments of rock on the surface, at once arrests attention, as indicative of the vicinity of that rock *in situ*. The observer traverses the ground in all directions in search of any projecting knob of the actual rock itself. Failing to find it, he notes the position of these angular chips, and tries whether they can be traced further, so as to indicate by their distribution at the surface the probable trend of the solid rock underneath. In ascending a hill-side so covered with trains of detritus or vegetation that no rock can be seen in place, the geologist may learn much regarding the concealed rocks by examining the *débris*. He knows that the fragments of stone have rolled down, and not up. When, therefore, in his ascent, he observes that the angular chips of some particular rock, abundant enough below, no longer appear, he surmises that he must have crossed the limits of the solid rock which furnished the fragments. If in the course of subsequent examination he discovers that these fragments disappear about the same line all along the hill, he may regard his first surmise as probably correct, and draw a boundary-line accordingly, even although he may never have seen the actual rock itself *in situ*.

Again, in the ascent of streams, similar close observation and sagacious inference will often go far to supply the place of actual sections of rock. The use of the evidence in these cases, however, requires still more caution than on the bare hillside, because the tendency of running water is to round the rock fragments exposed to it, and hence in the channel of a brook or river, it may not be always possible to distinguish between the pebbles which have come as angular fragments from neighbouring solid rocks, and have been rounded by the attrition of the brook or river itself, and those which, derived from some old gravel, were already rounded and water-worn before they tumbled into the channel. A great abundance of fragments of one particular variety of rock, however, would suggest that they had not been washed out of some gravel bed, but had been derived from the waste of a solid rock lying somewhat further up in the drainage basin of the stream. In such a case, moreover, the proportion of these fragments in the channel would probably be found to increase as the stream was traced upwards. Perhaps, at the same time, they might be observed to become larger in size and less water-worn. If they should suddenly cease, the observer ought at once to note the fact, as possibly indicating that the rock does not occur higher up, but has its upper limit somewhere near the point where the fragments in the stream disappear. While these particular rock-chips cease, others of some different rock may be found to increase in number, and another zone of rock may be shown and traced in a similar way.

In many parts of the country where, owing to the depth to which the rocks have decayed from the surface downward, no satisfactory exposures of them can be found on the fields, or even in the valleys and brooks, sections may be detected on the roads where the superficial cover of disintegrated material has been worn down or cut through.

In nothing is the highest type of a field-geologist better displayed than in the exhaustiveness and sagacity with which, in the absence of all other evidence, these various little indications of the geology of a district are sought for, found, and marshalled in their proper places, so as to bear witness to the distribution and probable structure of the rocks. Such an observer is able in many cases to trace lines, with a near approach to accuracy, over ground which a less skilled student would pronounce to be a blank.

It must often happen, however, that the ground is so obscured by superficial accumulations, such as vegetation, soil, gravel, and clay, that no indication whatever can for considerable intervals be found as to the nature of the solid rocks underneath. Under these circumstances the geologist, when no boring or mining operations are at his service, must do the best he can, by examining all the surrounding ground, to determine what lies below the concealed area. And in the great majority of cases he can form a tolerably correct surmise as to the general nature and disposition of the rocks. To do this requires some knowledge of geological structure, which we shall consider in the following chapter.

CHAPTER IX

THE UNRAVELLING OF GEOLOGICAL STRUCTURE—DIP, STRIKE, OUTCROP

If we could only recognise rocks where they are actually seen, but form no satisfactory conclusion regarding their distribution under a concealing mantle of vegetation or superficial detritus; if we could tell the arrangement and measure the thickness of strata only at the surface, but offer no opinion as to the prolongation of these strata underground, we should never know much about the crust of the earth, and certainly could do comparatively little to advance geological inquiry. Fortunately it is not only possible but comparatively easy to pronounce upon the subterranean arrangement of rocks from indications obtainable at the surface. We seldom need to bore or dig. It is usually enough if we can avail ourselves of the surface evidence, and gain from it information respecting the probable arrangement of the rocks below, or in other words, the geological structure of the ground. How this is done, let us now proceed to consider.

Horizontal Strata—Outcrop.—In a region where the rocks are all horizontal, only the uppermost stratum may be seen, in which case an example of extreme simplicity of structure would result. There would then be no outcrop or exposed edge of any stratum to be traced, unless the surface of the ground should be so uneven as to expose the edges of lower strata. Except in tracts of low alluvium, however, horizontal strata have usually been more or less trenched by valleys and ravines, so that sections are laid bare of the underlying rocks. Further, the surface of the country seldom rigidly corresponds with the surface of a stratum, but has been worn across it, so as here and there to leave "outliers" or outstanding portions of this upper stratum, and to lay bare the strata below. Where this has taken place in bare hilly land, with abundance of exposures of the rocks, although the geological structure is still of the simplest

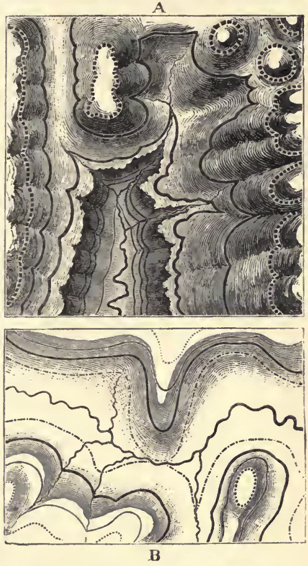


FIG. 24.—Sinuous outcrops of horizontal strata depending on inequalities of surface.

possible kind, considerable practice and skill may be needed to follow the exposed edges or outcrops of the strata, and to delineate them accurately, and at the same time artistically, upon a map. The accompanying drawings (Fig. 24) may serve to illustrate how very tortuous the outcrops of perfectly horizontal beds may be, should the ground be much varied in outline, and especially if it be diversified with wide and deep valleys. In the uppermost map (A) a representation is given of horizontal rocks deeply trenched by valleys and ravines. In the lower map (B) the inequalities of the ground are much less, yet even in such a gently undulating district the outcrops of horizontal strata may evidently run in remarkably sinuous lines. In a high plateau region of horizontal strata which has been deeply trenched by ravines and where endless outliers have been left isolated, the mapping even of this simple structure may involve infinite labour from the multiplicity of lines of outcrop that have been exposed by the denudation. But if the mapping be done carefully and accurately it may serve as a model from which the topography of the country will be at once grasped by the eye. The singularly dissected plateau-regions of South Africa furnish admirable illustrations of this kind of geological structure and resulting scenery.

I have used the word artistic with reference to the tracing of geological boundary-lines, and have done so advisedly. Where the rocks are all visible, the observer has only to follow nature, and the more faithfully he does so, the more graceful will his lines probably be. The curves produced by denudation, though often complex, are never awkward and inharmonious. Where the rocks are not seen, and where therefore the position of the boundary-lines must be inferred, the surveyor will follow the analogies of his district, and run his boundaries with the same kind of flowing lines which he sees them to possess where they can be actually examined. Two men may map the same piece of ground quite correctly as regards its general structure, but the map of the one will show by the complexity of its lines and the fidelity with which they follow the varieties of the surface configuration, how faithfully and skilfully the work has been done; while the map of the other will indicate that its author, though marking correctly the general structure, has failed to recognise, or, at least, to express the relations of that structure to external form. The former map will in most cases be a far more artistic as well as accurate production than the latter. Not only in such simple work as the tracing of horizontal strata, but in all the details of geological map-making, the artistic eye and hand have scope to show their presence; to the great advantage of the maps to which they are applied.

Inclined Strata—Dip.—Instead of lying quite flat, however, stratified rocks are usually inclined to the horizon. This inclination, called their *dip*, is measured

FIG. 25.—True dip concealed by superficial disturbance of the strata.

as to its direction by the compass, as to its angle by the clinometer. In determining these points it is always desirable to see more than a mere projecting edge of rock, for sometimes what seems to be the dip in such a case is deceptive. In Fig. 25, for instance, the rocks are really inclined at a high angle towards the left hand. Yet if seen merely at the surface where they have been bent back (by the slide of rubbish down-hill, or by a grinding mass of ice or other superficial agent) they might be supposed to be dipping from left to right. To be sure of the true angle and direction, we must not be content

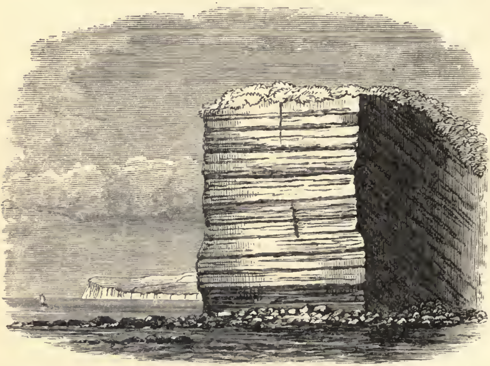


FIG. 26.—Inclined strata appearing horizontal when exposed at a right angle to the dip.

with one small face of rock, but should go round a section until we determine the point satisfactorily. A face of rock, for instance, seen from one side, as in Fig. 26, may appear to be made of horizontal strata, which from another point of view are found to be considerably inclined. The direction of dip will always be at a right angle to the line along which the edges of the inclined beds appear horizontal. Failing, therefore, to find any actual section along the true line of dip, we should so place ourselves as to have the exposed edges of the strata running in horizontal bars in front of us. We may then take the direction of dip with the compass, and determine from the mean of a number of observations taken with the clinometer on projecting ledges what must be the general average angle of dip. The best measurements of the angle of dip are made when we can place ourselves some little distance in front of a face of rock which has been cut in the true direction of dip. We can then place the clinometer in front of our eye, and make its edge coincide with the line of a particular stratum many yards in extent. Thus in one single observation we obviate the risks of error where only small ledges of the inclined beds can be used. Where the true dip cannot be directly measured we may, by measuring the apparent dip of two faces of rock inclined at a considerable angle to each other, obtain the true dip by calculation.[1]

Having ascertained these particulars, we insert the information in our note-book or map. The use of a map for the registering of observations on geological structure requires an amount of precision which might not be thought needful for the pages of a note-book, and secures in consequence the most careful and exhaustive kind of field-work. I shall, therefore, suppose in what I have to

[1] Rules are given for measuring or calculating the dip. (See Green's *Geology*, p. 461.) For almost all practical purposes, however, a good field-geologist can get his angle with the clinometer in the field by selecting, as he learns how to do, his points of observation.

say on this part of my subject, that we are required not only to make observations on geological structure, but to formulate them on paper, and to construct the geological map of a region.

The usual sign used on geological maps to express the dip of strata is an arrow pointing in the direction of inclination (the direction being found on paper by help of an ordinary protractor), with the number of degrees of angle shown in figures at the side of it. We place, therefore, an arrow at each point on the map where we ascertain the dip of strata. A glance at the map (Figs. 27 and 28) will show how this is done. Each arrow marks the site of the observation, and with its accompanying figures records the result. Where possible we enter beside the arrow some symbols, or contracted writing, to describe the nature of the rock, or any other particulars which it seems desirable to record. Further detail, where required, finds its place in the note-book.

Selection of Horizons—Mapping of Outcrop.—As it is impossible on any ordinary map to represent every bed of rock, the geologist must decide what beds should be selected to be traced out. This cannot always be done until considerable progress has been made with the work. The selection must depend not merely upon the geological or industrial importance of the strata, but also, and not less frequently, upon the extent to which they are exposed and capable of being followed across the district. A particular stratum of no special interest in itself may come to have a high importance as a geological horizon or platform if it is easily recognisable, and from its thickness, hardness, or other peculiarity, stands out so prominently that it can be satisfactorily traced from point to point for a long distance. Such stratigraphically serviceable bands may be found in most districts of stratified rocks. Great assistance in the tracing of horizons is likewise afforded by organic remains, as has been already pointed out. A particular stratum, even when thin and otherwise of no apparent importance, may acquire a high value if it is charged with fossils, and can be recognised over a wide area.

The outcrop may be marked at any particular locality by a short line beside the dip-arrow, or if the outcrop be a broad one, by two lines, one marking the base, the other the top of the band. The space between two such lines—in other words, the breadth of the outcrop—is determined by the thickness of the bed or beds, their angle of inclination, and the slope or contour of the ground. Among a series of vertical strata the breadth of the outcrop of a bed corresponds exactly with the true thickness of that bed. The more the angle of inclination lessens, the broader does the outcrop at the surface become. Hence, in tracing such a band across a country, attention must constantly be given to the variations of angle in the dip. Where the dip increases the band narrows in breadth; where the dip lessens the band widens. This is best seen on level or gently undulating ground; it is apt to be less distinctly shown where the ground is very uneven, and where therefore constant modifications of the line of outcrop are produced, as we have seen to be the case with horizontal strata. When strata are vertical no amount of surface irregularity makes any difference on the width or direction of their

FIG. 27.—Map showing the data from which a completed geological map is made. (The top of the map is north.)

outcrop. They are apt in that position to run on for some distance with little deviation of direction, so that the outcrop of one of them might be marked by a straight bar or line (Fig. 27). The influence of the form of the ground tells more and more upon the outcrop in proportion as the strata approach the horizontal.

Strike.—The outcrop of a stratum is the line which that stratum makes with the surface of the ground. This term "outcrop" is often spoken of as if it were the same as the "strike." The latter word is applied to a line drawn perpendicular to the direction of dip. It is the line made by a stratum with the horizon, and shows the general or average direction of that stratum across the country. On a perfectly level piece of ground strike and outcrop must obviously coincide, and there must likewise be a complete coincidence among vertical strata. The more irregular the surface, and the less inclined the strata, the further must strike and outcrop depart from each other.

Relation of Strike to Dip.—There is a further relation to be noted as we proceed, viz.—the constant dependence of the direction of strike upon that of dip, and the consequent changes of strike as the direction of dip varies. The strike is of course a mathematical line cutting the dip at a right angle. If the dip is east or west, the strike must be north and south; if the dip is north or south, the strike must be east and west. It must not be supposed, however, that the line of strike is always, or even most commonly, a straight one. It can only be so as long as the direction of dip continues unchanged. But a comparatively brief experience in the field suffices to show how constantly the dip of strata varies, now to one side, now to another, every such variation producing a corresponding change upon the line of strike. Where the deviations are slight, and of local character, while the mean direction of inclination remains the same, we take that mean direction as governing the strike (as at band F in Fig. 28). Where, on the other hand, the dip is to different points of the compass in succession over wide spaces, we connect the arrows on our map by lines (as in band G in Fig. 28), and find that the strike becomes a curved, and even, it may be, a very sinuous one.

Difference between Outcrop and Strike.—Unless these two terms, already explained, are clearly distinguished in constructing a geological map, we shall either lose the impression of the external form of the ground, which a correctly-traced outcrop so often vividly conveys, or we shall be in danger of regarding the dip as constantly changing, and the strata, though perhaps nearly flat, as extensively disturbed. Looking at any good geological map of England and Wales, the reader will notice that the bands of the Oolitic and Cretaceous rocks, while retaining a tolerably persistent strike from south-west to north-east, across the breadth of the country, present most sinuous and irregular edges. The direction of the dip, and consequently the trend of the strike, change but little, yet it will be observed that the outcrop is continually shifting to and fro. The strata really follow each other in parallel bands. If we could plane down the whole country to a dead level, these bands would be marked by alternate approximately straight and parallel strips of clay, limestones, and sandy rocks. But instead of being a flat, the country undulates; hence a series of gently inclined rocks of various degrees of durability necessarily gives a diversified set of outcrops. No better illustration could be studied of the difference between outcrop and strike, and of the marked influence even of small ridges and hollows and shallow valleys upon the outcrop of strata, where the angle of dip is low. The main facts to be expressed upon the map of such a tract of country are, that the formations follow each other in a certain order, and cross the region in a certain direction. Of course we might record these facts by simply drawing straight parallel strips across the map, each marking the general position and relative breadth of one of the formations. This was the way in which the old geological maps on a small scale were constructed, and indeed when the scale is minute, no other mode of representation is possible. The map of England and Wales in Bakewell's *Geology*, even so late as the edition of 1838, may serve as an example. But by such a style of mapping we entirely lose, as I have just said, one of the valuable features of a geological map—the relation between the external form of the ground and the nature and grouping of the rocks below, that is, between scenery and geological structure. It may readily be believed that this is too important a relation to be ignored without great disadvantage when the scale of the map at all permits it to be expressed. Besides, the omission deprives the map of the chief feature by which the work of a skilled and artistic observer is distinguished, whose eye and hand are quick to seize upon and delineate the characteristic varieties of form which geological boundaries assume as the surface of a country changes from plain to hill, and as the rocks themselves alter in thickness and position.

Numerous illustrations of the applicability of this principle will occur to every observer in the field. If, for example, he stands at the higher margin of a rocky valley, along the sides of which inclined beds of sandstone, limestone, or other stratified rocks are exposed, dipping gently down the valley, he observes that the outcrop of each bed does not go straight across from the top of the declivity to the corresponding outcrop on the opposite side. On the contrary, it descends the slope in a slant until it reaches the bottom of the valley, when it turns and mounts the opposite slope, thus forming a V-shaped indentation on the general line of strike (as in the valleys on the south side of the map, Figs. 27 and 28). Now the manner in which these windings of the outcrop of inclined strata and their relation to the form of the ground are expressed upon the geological map is a good test of the skill and delicacy which I have insisted upon as so desirable in the map-work of a field-geologist. Many observers are content to draw the lines of outcrop as straight bars across the valleys, thus making them coincident with the strike. On maps of a small scale, indeed, as above remarked, nothing else is possible. But where the scale admits of it, much advantage will be gained by faithfully depicting the curving outcrops. The map then tells its story at once, and brings the relation between geological structure and external form almost as vividly before the eye as a well-made model could do.

Construction of a Geological Map.—In order to show the application of the foregoing observations, two diagrams (Figs. 27 and 28) are here given. In Fig. 27 an attempt is made to convey some idea of the way in which the required data are compiled and recorded in the construction of a geological map. The shaded parts of that figure represent what is actually seen by the geologist; over the blank portions he is supposed to have been unable to find any rock *in situ*. Fig. 28 shows the map as filled in and completed from these data. I shall have occasion to make frequent references to these maps in what follows.

It will be noticed that most of the observations occur along the stream-courses, these being the most frequent natural lines of section. At each point where the dip of strata has been taken, an arrow and number mark the direction and angle. The more important or stratigraphically serviceable beds have their outcrop marked in decided lines where it is actually seen. When the same stratum can be recognised in two parallel or adjacent streams or valleys, the outcrop may be drawn across the intervening ground, which of course should itself be searched for traces of the desired line. Where there can be no doubt as to the direction and position of the outcrop, it may be drawn as a continuous line or band. Where, however, though it is known to occur within certain limits, some doubt may exist as to its exact position, it should be expressed by broken or dotted lines.

Establishing a Stratigraphical order of Succession.—It will be seen from the map that in the streams at the

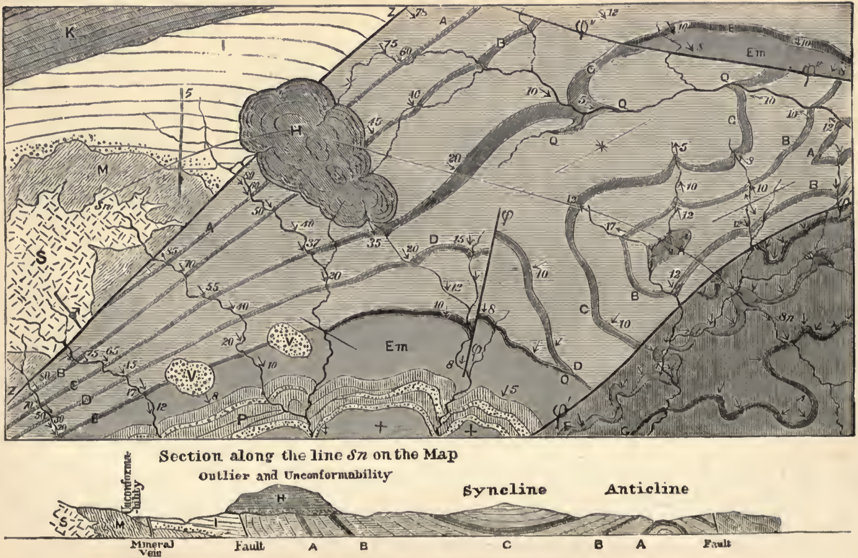


FIG. 28.—Completed geological map and section.

lower part of the left side, the same beds are recognisable, following and dipping under each other at corresponding intervals. In other words, the order of succession is found to be the same in the different streams. Bed *A* after an interval is followed by bed *B*, bed *B* by bed *C*, and so on. Even, therefore, where a blank space occurs, and, owing to some surface accumulation, a particular bed may not be visible in one of the lines of section, we can be tolerably sure of the place where, judging from the strata above and below, it would be seen if it came to the surface. We do not hesitate, therefore, to draw dotted lines across that place to indicate our belief. A geological map is thus derived partly from what is seen, and partly from what can be legitimately inferred.

I would further direct attention to the fact that while the order in which the beds occur remains the same in all the streams upon our map (Figs. 27 and 28), the spaces between them vary considerably. This difference may arise from one or other of three causes; either (1) variation in angle of dip, or (2) variation in thickness of strata, or (3) inequalities in the level of the ground. We have already considered the effect of a decrease of inclination in increasing the breadth of a stratum or series of strata at the surface of the ground. It is further evident that if the mass of strata between two known beds should swell out or diminish, the breadth of the space between their respective outcrops must correspondingly vary. Inequalities of the surface must likewise influence, as we have seen, not only the direction of the outcrops, but also their breadth. Where, therefore, the angle of dip does not change, and the surface of the ground presents no marked inequalities, but where, nevertheless, a decided widening or narrowing of the interval between two outcrops occurs, we infer with confidence that the intermediate strata must increase or diminish in thickness.

Estimation of Thickness of Strata.—When the angles of dip have been observed along a line perpendicular to the strike, it is easy to calculate what the thickness of rock must be in any given interval of the section, or to obtain it by using the protractor. This is most conveniently done at home, where the observer can collect his notes and protract the angles he has taken in the field. It is useful, however, to have a ready means of estimating thickness, and in this respect the following rule, given many years ago by Maclaren,[1] will be found of service. If the breadth of inclined strata is measured across their outcrop at right angles to the strike, their true thickness will be equal to $\frac{1}{12}$th of their breadth at the surface for every 5° of dip. Or it may be put thus: divide 60 by the angle of dip, and the fraction is obtained which expresses the thickness. Thus, suppose a mass of strata measures across the strike, 1200 feet, and is uniformly inclined at an angle of 5°, its real thickness will be $\frac{1}{12}$th, or 100 feet; at 10° the thickness will be $\frac{1}{6}$th, or 200 feet; at 15° it will be $\frac{1}{4}$th, or 300 feet; at 20°, $\frac{1}{3}$d, or 400 feet. This rule is very nearly accurate for inclinations up to 45°.

Thinning away of Strata—Overlap.—It sometimes happens that two lines of outcrop come together, owing to the complete thinning away of the intermediate strata,

[1] Charles Maclaren's *Geology of Fife and the Lothians*, p. xv.

and the conjoined outcrops may then be traceable for a long distance without further change. Instances of this kind sometimes occur among coal-seams. The higher portions of a series of strata now and then steal over the lower, so as to constitute what is termed

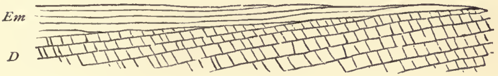


FIG. 29.—Section of an overlap and unconformability.

an "overlap." This structure cannot always be expressed in plan upon a map, but is made clear by a section. On the map (Fig. 28) the upper portions of the group *Em* overlaps upon group *D* in the neighbourhood of the locality marked *O*. A section of this part of the district would be as in Fig. 29.

This structure may frequently be met with along the margins of formations deposited in tracts which were

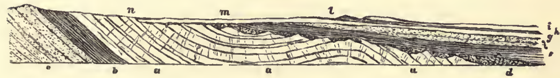


FIG. 30.—Overlap and unconformability, Mendip Hills (De la Beche). *c*, Old Red Sandstone; *b*, Lower Limestone Shale; *a*, *a*, Carboniferous Limestone; *d*, beach deposits of Lower Jurassic age passing up into *e* Lias; *f*, Sands of Inferior Oolite, which are overlapped by *g*, *n*, Inferior Oolite; *h*, *l*, clay, and *i*, limestone of Fuller's earth.

undergoing gradual submergence. As the land sank, successive zones were carried down beneath the sea, and the later deposits of the sea-floor were prolonged further and further beyond the limits of the earlier ones.

The accompanying section (Fig. 30) shows very clearly an overlap among the Jurassic beds, all of which lie unconformably on the Palæozoic rocks.

Unconformability.—In an overlap the strata are parts of one continuous unbroken series, the formation of which does not appear to have been interrupted by any great physical disturbance, nor even, in many cases, by marked change of any kind in the general conditions of deposit. The strata are throughout conformable among themselves; at least no sensible unconformability can be detected between any portions of them. But where the accumulation of a group of rocks has been succeeded by elevation, exposure, and denudation, the next set of strata laid down on this disturbed and denuded group will rest upon it unconformably. Thus in Fig. 30 the Secondary formations (*d*—*i*) lie unconformably upon the Palæozoic rocks (*a*—*c*). It is not, however, necessary, though it is usual, for the older rocks to have been disturbed from their original horizontality. They may obviously have been equably upraised, and, after being exposed to denudation, may have been gently depressed again without sensibly losing their original horizontality. But such equable elevation and depression are not common. Some tilt has generally been given to the strata, and consequently the overlying rocks rest transgressively upon their upturned and worn edges.

An unconformable junction or unconformability, as it is termed, is of the highest importance in the geological structure of a district. It marks one of the great gaps or intervals in geological history. The observer ought to spare no pains to collect all the available data in every case where he has reason to suspect the existence of such a structure.

An extreme case presents little difficulty. It can be expressed so clearly upon a map as at once to tell its own story. Thus in Fig. 28 the sheet of rock *H* evidently forms a flat unconformable cake lying upon inclined and denuded strata. A section across this cake would disclose an abrupt junction of the horizontal beds on the edges of the steep and vertical series. But many cases occur where the discordance between the two series is far less strong, where indeed much care and labour may be required to make out an unconformability at all. For here again, as in the case of faults, the actual line of contact between two groups of rocks is comparatively seldom seen. We must usually infer from their relative dip and strike and their lithological characters whether or not they are separated by an unconformability. In the diagram we have already used so much (Fig. 28) another and less violent unconformability is shown towards the north-west corner, where the series of beds *K* steals over the denuded outcrops of the series *I*.

A special interest attaches to unconformabilities, inasmuch as they enable the geologist to recover the land surfaces of former periods. Some wonderful examples of this revelation of ancient topography are to be met with in the west of the counties of Ross and Sutherland, where groups of mountains, older than the very oldest of the fossiliferous formations of Britain, once buried under piles of red sandstone and conglomerate, are now in course of being once more laid bare by the denudation of the younger unconformable formation

(Fig. 31). Some of these primeval mountains thus revealed are more than 3000 feet high.

In collecting evidence on the subject of a supposed unconformability the observer should endeavour to realise to himself what must have been the contour of the ground at the time when the overlying rocks were

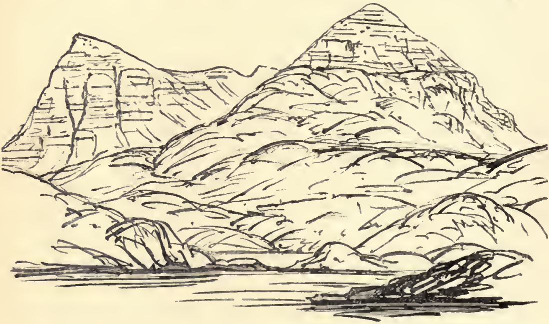


FIG. 31.—View of Quinaig, Sutherland. The Archæan gneiss rises in the right-hand part of the mountain into a hill some 700 feet high, which is capped and still partially surrounded by nearly flat sandstone and conglomerate.

accumulated. He may in this way sometimes be led to see that his suspected unconformability is extremely unlikely, or physically impossible. As a curious illustration of the consequences of the want of this precaution Fig. 32 is here inserted from a published geological section. The horizontal distance represented is about six miles, and as the upper rocks are made to dip at angles of between 40° and 50°, there must be a mass of them somewhere about four and a half miles thick. If we suppose them to have been originally perfectly horizontal, they must have been laid down against the slopes of a mountain about four and a half miles high; or if they sloped gently away from the underlying rocks, the height of the mountain must have been still greater. But not only must a stupendous mountain have been tilted round so as to lie on its side; the whole of the later rocks must have been removed except a narrow cake cut across the bedding parallel with the original slope of the mountain. In reality there are not two

FIG. 32.—Portion of a geological section with an impossible unconformability.

sets of rocks in the line of section. The whole is one, subject here and there to local crumpling and faulting, as might have been seen by more careful and extended observation.

Where no satisfactory evidence can be obtained of the stratigraphical relations of two groups of rocks, that is, where neither of them exhibits its dip and strike in such a way as to show whether or not they are unconformable, proofs of a discordance between them can sometimes be found in the presence of conglomerates in the one series derived from rocks that occur in place in the other. This kind of proof may undoubtedly in many cases be taken to establish an unconformability. But it is not always sufficient. For example, a volcanic conglomerate derived mainly from the detritus of an underlying lava may occur in a perfectly conformable succession of rocks and need not mark any break in the geological sequence. Conglomerates have often been assumed to be proofs of unconformability. Unquestionably they frequently occur at an unconformable junction; but they appear also in the midst of the most perfectly conformable strata, as may be illustrated by many examples among the Palæozoic rocks of Britain. In Fig. 33, for example, a section is given of about 1500 feet of the Lower Old Red Sandstone in Midlothian. It will be seen that high above the massive bottom conglomerate other coarse conglomerates occur at different horizons in an entirely conformable succession of strata hundreds of feet above the base.

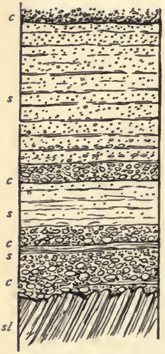


FIG. 33.—Section of a portion of the Lower Old Red Sandstone, Pentland Hills, *sl*, Upper Silurian shale, covered unconformably by *c*, *c*, *c*, conglomerate, and *s*, *s*, *s*, sandstone and pebbly grits.

In most cases it is possible so to express an unconformable junction upon the map as to make it readily apparent to the geologist. It should be the aim of the surveyor to neglect no item of evidence which will enable him to do this; for the more perfectly his map is self-interpreting, the more useful will it be. Hence where, as is often the case, the ground is obscured by surface-accumulations, and a little liberty of choice is left to him as to the precise course along which to place his line of unconformability, he will draw this line in such a way as to show as clearly as may be that it is not a fault or an ordinary conformable junction.

In some districts, particularly in those where older formations are covered by more recent superficial accumu-

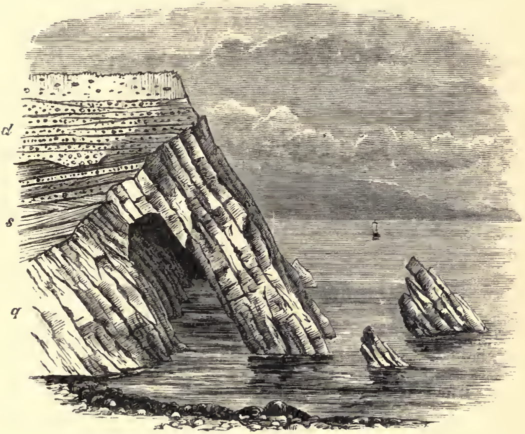


FIG. 34.—Double unconformability at Cullen, Banffshire.

lations, a double unconformability may often be seen. The accompanying diagram, for example (Fig. 34), represents what is exposed in a cliff section at Cullen, on the coast of Banffshire. The lowest formation consists of quartzite (*q*) in strata inclined at a high angle to the south-east. The upturned ends of these strata are unconformably overlain by red sandstones and conglomerates (*s*) dipping gently away towards the south-west, which are in turn unconformably covered by glacial clays and gravels (*d*). This is an interesting and instructive section, inasmuch as it teaches us how rash it would be to form any conclusion as to the relative length of the intervals of time represented by the amount of discordance between unconformable formations. The break between the quartzite and the red sandstones is apparently much more violent and complete than that between the sandstones and the glacial deposits. And yet there can be little doubt that in regard to geological age, the interval of time between the deposition of the quartzite and that of the sandstones was shorter than that between the sandstones and the overlying clays and gravels. It is evident indeed that sections might be found showing an apparently perfect conformability for a certain space between the sandstones and the glacial beds. Yet this local agreement in position would not be allowed to conceal the real and complete break between the two series of formations.

CHAPTER X

THE UNRAVELLING OF GEOLOGICAL STRUCTURE—FAULTS

We have been dealing hitherto only with such variations in the outcrop of strata as may arise from the form of the ground, from variations in the thickness of beds or from changes in the direction and angle of dip. But the outcrop is often broken completely across, and even removed entirely out of sight, by those dislocations in the earth's crust to which the name of "faults" has been given by geologists. These lines of fracture generally form few or no features at the surface, so that their existence would commonly not be suspected. They comparatively rarely appear in visible sections, but are apt rather to conceal themselves under surface accumulations, just at those points in a ravine or other natural section where we might hope to catch them. Yet they undoubtedly constitute one of the most important parts of the geological structure of a district or country, and should consequently be traced with the greatest care.

The learner may, perhaps, hesitate to believe that a geologist can satisfactorily trace a line of fracture which he never actually sees. But a little attention to this part of our subject will, I hope, convince him that the mere visible section of a fault on some cliff or shore does not afford by any means such clear evidence of its nature and effects as may be obtained from other parts of the region where it may not show itself at the surface at all. In fact, he might be deceived by a single section with a fault exposed in it, and might be led to regard that fault as an important and dominant one, while it might be only a secondary dislocation in the near neighbourhood of a great fracture, for which the evidence would be elsewhere obtainable, but which might never be seen itself. The actual position (within a few yards) of a large fault, its line across the country, its effect on the surface, its influence on geological structure, its amount of vertical displacement at different parts of its course—all this information may be admirably worked out, and yet the actual fracture may never be seen in any one single section on the ground. A visible exposure of the fracture would be interesting; it would give the exact position of the line at that particular place; but it would not be necessary to prove the existence of the fault, nor would it perhaps furnish any additional information of importance.

The geologist, therefore, constantly finds evidence of far more dislocations than he can actually see. Those which appear, sometimes commonly enough, on lines of cliff or coast-section, are apt to be but small and trifling. The larger faults—those which powerfully influence the geological structure of a country—are seldom to be caught in any such visible form. Now why is this? Several reasons may be assigned, each of weight.

First of all, it is evident that along lines of great dislocation there would naturally be a great deal of grinding and crushing of the fissure-walls. The broken rock in the line of fault crumbles down more than the solid rock on either side beyond it, or is more easily excavated and removed. So that whether on a cliff or on a flat surface, the actual fault is apt to be concealed by detritus. Then again, large faults often bring together rocks of considerably different degrees of durability. The less-lasting material decomposes, and its *débris* goes to cover the actual junction-line between the two forma-

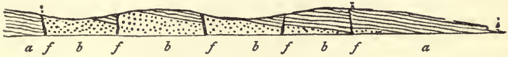


FIG. 35.—Section of Lias (*a*), and New Red Sandstone and marl (*b*), cut by fault (*f f*), near Watchet, Bristol Channel. (De la Beche.)

tions. Another reason may be sought in the extensive deposits of gravel, clay, or other superficial materials which are spread over the surface of a country and conceal the solid rocks. A line of fault is one of weakness, presenting facilities for attack by the denuding forces whereby it is hollowed out, so as to become a receptacle for these superficial deposits.

In regions where the solid rocks are not buried under superficial accumulations, but come up tolerably bare to the surface, examples not infrequently occur of faults which, though not actually visible themselves, show their presence and trend by their influence on the topography of the ground. Sometimes their trend is marked by a gash or hollow: at other times by a deflection in the line of a valley or ravine. In many cases the rocks on one side, being harder than those on the other, stand up as a long steep bank or sloping hill-front, above the lower ground, which is underlain by the more destructible materials. Yet in all these and other instances, the actual dislocations are seldom to be seen.

When we consider, however, the vast number of faults that traverse the crust of the earth, as is so impressively brought home to the mind by mining operations, it must be admitted that in the vast majority of cases, they produce little or no visible change on the contour of the surface. Had they been left uncontrolled by any other influence, they might have been expected to cut up the ground into innumerable irregular segments, standing at different levels and bounded by steep walls of rock. That such a topography does not exist proves how extensively the ground has everywhere been planed down by denuding agencies. In the foregoing section (Fig. 35), for example, five faults are shown; yet in no single case does the line of dislocation betray itself by any marked surface feature.

In the consideration of faults, therefore, two questions obviously arise. How does a geologist recognise faults when he sees them? and how does he prove their existence when he does not, and cannot, see them?

I need not enter into any detailed answer to the first of these questions. The inspection of the section of a fault in nature will tell more in a few minutes than could be learnt from description in an hour, and the lesson so received will be better remembered. A fault is not usually vertical but inclined at a high angle. The rocks are commonly somewhat shattered on one or on both sides, the central parts of the fracture being filled with the broken rubbish. The breadth of broken material may vary up to a mass of many yards. If, on the face of a cliff, two different sets of rocks are brought against each other along a steep line of junction, where they are both jumbled and broken, that line will almost certainly be found to be a fault (Fig. 36). But examples will be met

FIG. 36.—Section of a fault.

with where the two sides come together with a clean sharp line, as if they had been sliced through with a knife.

The inclination of the sides of the fault is termed its *hade*, and in normal faults slopes away from the side which has been pushed up, or in the direction of that which has gone down. This is a useful fact, as it enables an observer to note which is the up-throw or down-throw side of a fault. The hade ought therefore always to be noted, and in mining districts its angle of inclination may be conveniently recorded to explain the position of the same dislocation in the underground workings.

Unless the same bed can be recognised on both sides of a fault as exposed in a cliff or other section, it is evident that the fault at that particular place does not reveal the extent of its displacement. It would not, in such a case, be safe to pronounce the fault to be large or small in the amount of its throw, unless we had other evidence by which to identify the beds on either side. A fault with a considerable amount of displacement may make little show in a cliff, while on the other hand, one which, to judge from the jumbled and fractured ends of the beds on either side, might be supposed to be a powerful dislocation, may be found to be of comparatively slight importance. I may cite in illustration, the section exposed on the cliff near Stonehaven in Kincardineshire, where one of the most notable faults in Great Britain runs out to sea. This fault lies between the ancient crystalline rocks of the Highlands and the red sandstones and conglomerates of the Lowlands of Scotland. So powerful have been its effects that the strata on the Lowland side have been thrown on end for a distance of two miles back from the line of fracture, so as to stand upright along the coast-cliffs, like books on a library shelf. Yet at the actual point where the fault reaches the sea and is cut in section by the cliff, it does not appear as a line of shattered rock. On the contrary, no one, placed upon the spot, would at first be likely to suspect the existence of a fault at all. The red sandstone and the reddened Highland slates have been so compressed and, as it were, welded into each other, that some care is required to trace the demarcation between them.

Let us consider the nature of the evidence from which the existence and position of a fault are inferred, though the actual dislocation itself does not appear in any exposure of rock. The upper part of the earth's crust for a variable depth is traversed by a circulation of water which, descending from the surface and performing a

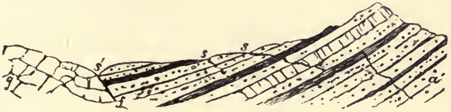


FIG. 37.—Fault (*f*) marked by the rise of springs (*s'*) at the surface.

circuitous underground journey, comes out again in springs (*s*, *s*, *s'*, Fig. 37. See also p. 97). The divisional planes whereby all rocks are marked serve as channels along which the water oozes or flows. Of these planes none offer such ready and abundant means of escape to the water as lines of fault (*f*, Fig. 37). Hence in some districts the faults are traceable at the surface by lines of springs. Without some knowledge of the country, we should not indeed be justified in inferring the existence of a fault merely from finding a linear series of springs. These might arise along the boundary between two different beds or sets of beds (see Fig. 23). The springs which issue at the base of the English Chalk are an illustration. But if, having ascertained that there is no such water-bearing boundary-line in the district, we come upon a marked line of springs, we may surmise that they indicate the position of a fault, and we may use them in confirmation of other evidence bearing on the existence of that fault. In unravelling the geological structure of a country, the observer may thus often be able, by means of springs, to localise a line of fracture, the existence of which he can demonstrate otherwise.

FIG. 38.—Geological section showing how a prominent feature at the surface may be caused by the outcrop of a hard rock (*a*) intercalated among softer strata.

In the same way, a marked and abrupt change in the form of the ground along a definite line may serve to show the position of a fault. It is true that here again the junction of two rocks or two groups of rock of different durability, such as sandstone upon shale, or limestone upon sands and clays, may give rise to a long straight or curving escarpment or slope. The mere existence of such a long line of bank would not of itself justify any conclusion or inference as to a fault. In Fig. 38, for example, we see how a steep declivity is produced by the intercalation of a hard bed between others of a much softer nature. The underlying strata (*c*) being more easily worn away have, by their removal, deprived the thick, solid, overlying mass of its proper support. Hence slices of that mass from time to time slip off and cumber the base of the cliff with ruined blocks, which tend to arrest the progress of decay until they themselves are gradually split up by the weather and removed.

Nevertheless, such abrupt changes of contour, taken in conjunction with other facts, may often be made to help in proving the existence of faults. Marked forms of ground have always some geological explanation. It is the province of the field-geologist to study them in connection with their causes, and to make use of them in elucidating the structure of the rocks and the history of the physical geography of a country.

But by far the most important and satisfactory evidence for the existence and effects of faults is furnished by the grouping of the rocks with reference to each other, and can only be put together when that grouping has been examined with some care, in other words, when some progress has been made in unravelling the geological structure of the locality. The nature of this evidence will be most satisfactorily followed by reference once more to the map in Figs. 27 and 28.

It will be observed that several lines of fault are shown upon that map. Look first at that which crosses the streams on the left or west side (*Z*, *Z*). In ascending the most westerly of these streams we notice that at first the rocks consist of various sedimentary deposits—sandstones, shales, and limestones. These strata dip toward the south-east, and their angle of inclination gradually rises as we proceed up the stream, until at the last place where they are seen, they stand at an angle of 80°. A short way higher up, we encounter rocks of an entirely different character; let us suppose them to be granite and crystalline metamorphic rocks (*S*, *M*). The gradual rise of angle and the almost vertical position of the strata would be regarded as sufficient to indicate the existence of a line of fault between the stratified rocks and the crystalline masses. The sections in the next streams are similar. It will be observed that while the general order of the strata is the same as we go eastward, lower and lower portions of them successively come into view below the band *B*, which was the lowest definitely marked in the first section. In the third stream, a still lower band (*A*) makes its appearance, while in the fourth there emerges below *A* a yet greater breadth of underlying strata. It is by thus piecing different contiguous sections together that the order of strata in a district is made out. The angle of dip in the second stream rises as before towards the higher ground inland, until angles of 70° to 80° are reached. In the third stream similar evidence is obtained, only here a little ambiguity seems at first to arise from the fact that the strata, after gradually becoming vertical, dip as it were into or below the granite. This in reality is a reversal of dip. The strata have not only been thrown on end, but actually bent back upon themselves, so that a section of them at that place would show such an arrangement as is given in Fig. 39. No more convincing evidence of the existence of a powerful fault could be given.

Now, having put these various data upon our map, we see that the point of junction between the two kinds of rock crosses the streams in a tolerably straight north-easterly line. There cannot be any doubt that the junction is a fault; for 1st, there is no trace of any conglomerates or other indications of an original base to the formation, lying upon and wrapping round the granite; on the contrary, the remarkably straight boundary-line is not at all like that of an old shore or unconformable junction; 2d, there is no evidence of the granite having been intruded through the rocks. The latter show no granite veins or traces of alteration. 3rd, The disturbed vertical and even inverted position of the strata all along the straight line of junction proves that line to be a fault. 4th, The upturned strata are cut across obliquely by the junction-line, so that different horizons of them are successively brought against the crystalline rocks.

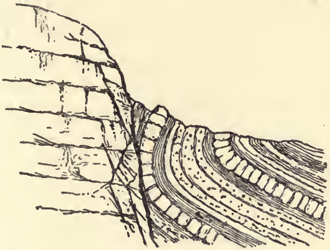


FIG. 39.—Section of fault with inverted beds on the down-throw side.

We cannot hesitate in such a case to treat the line as a fault, which we mark on the map by a strong pencil-line, at each point where there is good evidence as to its approximate or actual position. We should search for further traces of the line in the intermediate ground; and here may be realised the use of a line of springs, or of some definite bank or hollow on the surface of the ground, in enabling us to carry the line of the fault with confidence across a tract where no actual rock may be exposed. There could be, in the present instance, little hesitation in prolonging our strong pencil-line from point to point; if we felt any uncertainty as to its course through some part of the country, we should make the line there a broken or dotted one.

The side of up-throw or down-throw may either be fixed at once from our knowledge of the order of succession among the rocks, or may be determined at a later stage, as our acquaintance with the district increases. Thus, in the case which has just been under notice, if we knew that the granite series was older, that is, underlay the other, we should say that the up-throw of the fault was to the granite side. This direction might be marked on the map by a short bar placed perpendicular to the line of the fault, and on the down-throw side. In the completed map the fault might be shown by a strong black line or by a white line. The latter method is adopted on the maps of the Geological Survey of Great Britain, where fine lines of opaque Chinese-white are placed over the geological colours to mark the position of the faults.

From the example given in the diagram which we have been considering in detail (Figs. 27, 28), it appears that one indication of the proximity of a fault may be a rapid rise in the angle of inclination of strata. It is common to find the beds on the down-throw side bent up against the other side, and this upturning may extend for a few feet or for more than a mile. The amount of disturbance may be regarded as bearing on the whole a relation to the amount of vertical displacement of the fault; though to this conclusion there are many exceptions. The great fault already referred to as flanking the Scottish Highlands has placed the Old Red Sandstones and conglomerates on end for about two miles.

The beds on the up-throw side, on the other hand, may sometimes be observed to be bent down against a fault. This arrangement is of course what might have been looked for, but it does not always occur.

Another feature which, where no unconformability is to be suspected, may be regarded as a tolerably sound proof of the existence of a fault, consists in a complete divergence of strike between the formations on either side of a given line, or, in the common parlance of field-geologists, when one series of strata strikes at or against another. This may be most easily understood by reference to the diagram (Figs. 27 and 28). Towards the south-east portion of that map, two different sets of strata may be observed to crop up in the various streams and natural sections. The strike of one of these is at *D* and *C* nearly north-west. Towards the north-east, owing to a change in the direction of dip, the strike of the lower parts of the series (*C*, *B*) swings round, until at last it is E.N.E. and W.S.W. Now, unless some fault occurs, we may confidently expect that the strata which strike north-west and south-east will be found to continue southwards, though they may eventually participate in some other change of strike, and wheel round as before. If then in the line of their strike, and at a comparatively short distance in which they have no room to turn round, we encounter, as shown here, another and different series of rocks (*F* and *G*), we may reasonably infer that a fault intervenes, and may set about the search for further evidence of it. In the case supposed upon the map, the strata on the south side strike on the whole in a north-east and south-west direction. But close examination shows that some strata are cut out as they approach the junction-line; this plainly indicates the line to be one of dislocation.

A great many faults run with the dip, and are called *dip-faults* ($\phi\phi$ in Fig. 28); another series runs with the strike, forming *strike-faults* $\phi'\phi'$ in Fig. 28). But as dislocations may occur in any direction, and cross dip and strike at any angle, these two series are not very sharply marked off from, but may pass into each other, or the same dislocation may be a dip-fault when looked at from one side and a strike-fault when viewed from the other (as at $\phi''\phi''$ and z z in Fig. 28). Owing to the way in which denudation has smoothed down the surface of the ground, a dip-fault has the effect of shifting the outcrop of an inclined stratum so as to make it appear as if horizontally displaced. In the map (Fig. 28), for example, the beds D and E, dipping south, are traversed by a dip-fault with a down-throw to the east. The line of outcrop is consequently shifted northwards on the side of down-throw. If the beds had dipped northwards, then a down-throw to the east would have moved the outcrop southwards. A strike-fault, when it exactly coincides with the line of strike on both sides, makes no change in the line of outcrop, except in bringing two parallel bands closer together. It may, however, carry some important strata out of sight, or prevent them from ever being seen at the surface at all. Thus in the map (Fig. 28), the bed C is completely cut out against the strike-fault $\phi'\phi'$. If it were not seen at the surface elsewhere, its existence could not be known unless from some underground boring.

To judge of the character and effects of faults upon the geological structure of a country, the student should consult some good detailed maps, such as the large coal-field plans of the Geological Survey of Great Britain. It is good exercise, too, in the practical treatment of faults in field-geology, to study some coast-section where the strata are considerably faulted, and where they are exposed in plan upon the beach as well as in section upon the cliff. A river-ravine in summer weather, when the water is low, sometimes furnishes admirable lessons in this as well as in other branches of the subject.

Reversed Faults.—These are chiefly found among much disturbed and plicated rocks, where one side of a dislocation has been pushed over another. Lower strata are thus found overlying higher, and the hade, instead of pointing in the direction of down-throw, indicates that of up-throw. Examples of this kind of fault may be observed even in regions where the stratified formations remain over wide spaces undisturbed, but where they have locally been so much affected as to show that they have undergone a good deal of lateral pressure. Thus the Cretaceous and Tertiary groups of the south-east of England may be said to have suffered, on the whole, hardly any disturbance. Yet along some belts of ground they have been subjected to such terrestrial stresses as have caused them to be ridged up into sharp folds and to stand on end. In these tracts reversed faults may be observed among them.

Thrust-planes.—In districts where the rocks have suffered from great lateral pressure, the dislocations, which are forms of reversed faults, sometimes occur as inclined or undulating planes, the rocks above which have been pushed over those below. The horizontal displacement in such cases sometimes amounts to many

FIG. 40.—View of north face of Beinn a' Mhuinidh, Loch Maree, showing how a cake of Lewisian gneiss, etc., has been pushed along a thrust-plane, and now lies above Cambrian dolomite and quartzite. (A section across this hill-front is given in Fig. 41.)

miles. Not only have the rocks been ruptured, and older deep-seated masses been torn up and driven bodily over younger formations, but there has been at the same time such an amount of internal shearing as to crush the rocks into a finely-divided material (mylonite), and to give rise to a streaky arrangement of the broken particles, closely resembling the flow-structure of a lava. Coarse pegmatites may be traced until they pass into a substance that might easily be mistaken for an ancient rhyolite. In the crushed material new minerals have been sometimes so developed as to produce a true schist.

A thrust-plane may in places be almost horizontal, or may gently undulate over a distance of many miles. Hence it is sometimes cut by denudation into detached outliers; and the extraordinary result is thus obtained of hills and ridges capped by patches of displaced rock of vastly higher antiquity than those which underlie them.

The Cretaceous and Tertiary regions of the south

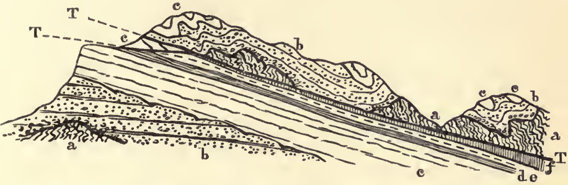


FIG. 41.—Section through Beinn a' Mhuinidh, Loch Maree, from north to south, *a a*, Lewisian gneiss; *b b*, Torridon sandstone; *c c*, Quartzite; *d*, "Fucoid beds"; *e*, serpulite grit; *f*, dolomite; T T, Thrust-plane.

of England, which have been cited as affording examples of reversed faults, furnish also some good illustrations of thrust-planes. On the foreshore at Eastbourne, on the chalk cliffs east of Swanage, and again to the west of Lulworth Cove, the Cretaceous formations may be seen to be traversed by lines of dislocation, sometimes nearly horizontal, where lower portions of the strata have been pushed up over higher.

Some of the most remarkable examples of this structure are those mapped in detail by the Geological Survey in the north-west of Scotland. Two figures are here inserted from that interesting but exceedingly complicated region. In Fig. 40 a view is given of the north front of an eminence 2231 feet high, at the upper end of Loch Maree in Ross-shire. The craggy ground forming the summit of the hill consists of Archæan (Lewisian) gneiss. The white cliff is formed of well-bedded quartzite, dipping gently southward under the summit of the hill, lying unconformably on the Torridon sandstone below, which in turn rests unconformably on the Lewisian gneiss. The structure of the hill is represented diagrammatically in Fig. 41. It will be observed that the portion of the older rocks displaced includes parts of the double unconformability, and that the rocks have been driven over and folded by a movement from S.E.[1]

[1] For an account of thrust-planes and numerous sections illustrating them see the Geological Survey Report in *Quart. Journ. Geol. Soc.* vol. xliv., 1888, p. 378.

CHAPTER XI

THE CURVATURE OF ROCKS

ALONG the limited exposures of strata usually visible, such as those in the bed of a stream, or a sea-shore, in a railway cutting or in a quarry, the planes of dip usually seem in section to be straight lines. Bed succeeds bed inclined at the same angle and forming a succession of parallel bands. But could we continue the sections downward beneath the surface, or see the rocks exposed on the bare

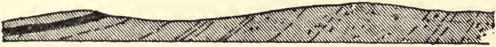


FIG. 42.—Section of inclined strata.

steep side of a great mountain, we should observe that though, when examined within the limited area of a few feet or yards, the beds look as if they sloped in straight stiff lines, in reality they are portions of great curves. That this must be so is made evident when we reflect on what must be the consequence of the variations of angle in the inclination of beds at the surface. Suppose, for example, that along the ravine of some river, or in any other natural or artificial opening, we encounter a succession of strata inclined as in Fig. 42. We cannot observe any visible indication of curvature in any of the beds, and yet, if we prolong the planes of dip above and below the surface (Fig. 43) we see at once that these must form a considerable curve, though with a radius so large that the bending does not appear within the narrow strip of rock exposed at the surface. Such indications of

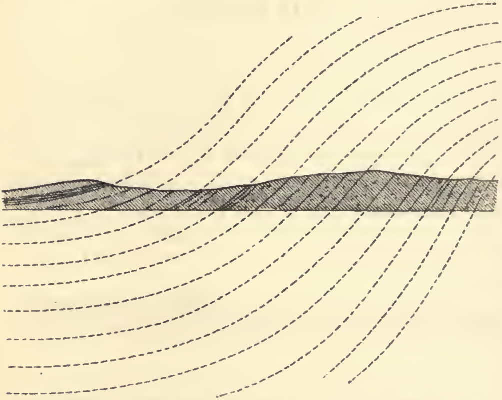


Fig. 43.—Section of inclined strata (as in Fig. 42), showing that they form part of a large curve.

endless undulations in the rocks of the earth's crust meet the field-geologist at every turn.

The larger curvatures can be best understood from a previous examination of those on a small scale, so often to be met with on coasts and in inland ravines. In such cases we may advance (from say *a* in Fig. 44) across the strike of beds dipping steadily towards us, and may not, from all that appears, suspect that any marked fold of the rocks is contained in the section. And yet on reaching *b* we should at once perceive that we were standing on the centre of an arch, saddle, or anticline,

FIG. 44.—Section of strata curved in an arch or Anticline.

and that if we went on towards *c* we should cross the same strata over again. Or, on the other hand, were we to traverse a succession of strata dipping continuously away from us, as from *a* to *b* in Fig. 45, and to come at last to a flattening of them and the commencement of a dip in the opposite direction, we should know that in this case the rocks had been folded into a basin, trough, or syncline.

The concealment of the central portion or axis of the fold where, on a small scale, as in the cases I have

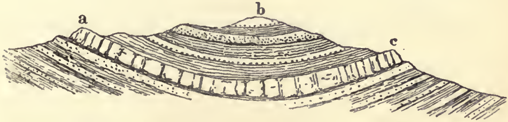


FIG. 45.—Section of strata curved in a trough or Syncline.

supposed, the actual bending of the rocks may be seen, does not make any difference in the interpretation to be put upon the contrary dips at *a* and *c* in Figs. 44 and 45. Indeed, in nature it is comparatively rare to see the actual central bending of the strata. In almost all cases, except the minor examples I have spoken of, the line of axis is determined from the angles taken among the inclined strata on either side. And here the advantage of one or more definite horizons is made strikingly apparent. If we can recognise the same stratum on both sides of a fold, we have in its position and angle of inclination a datum line from which to measure the extent of the fold. In Fig. 44, for example, if the bed marked *a c* can be identified on each side of the arch, we can estimate from the angles of inclination between it and the axis how high the arch must have been when this bed formed its crown, and what amount of material has since been removed. On the other hand it is easy in a similar way to calculate the depth of the trough (Fig. 45) from the centre down to the position of the stratum *a*, *c*.

We might expect that these curvatures of the solid rocks should always produce features at the surface; that the lines of anticlinal axis should correspond with ridges or hills, while those of synclinal folds should define the

FIG. 46.—Anticlines forming valleys; synclines forming hills.

trend of valleys. But it often, perhaps we may even say generally, happens that neither anticlines nor synclines produce any marked influence on the surface (Fig. 47). In walking over the two sections (Figs. 44 and 45), the observer not attending to the angles of inclination, would never suspect that he was crossing a geological ridge in the one case, and a geological valley in the other. When these curvatures affect the contour of the surface, they are apt to do so exactly in the opposite way to that which the learner might have anticipated. The anticlinal folds not unusually coincide with, and have given rise to, lines of valley; while the synclinal folds have originated lines of ridge or hill.

But the observer as he extends his experience will find

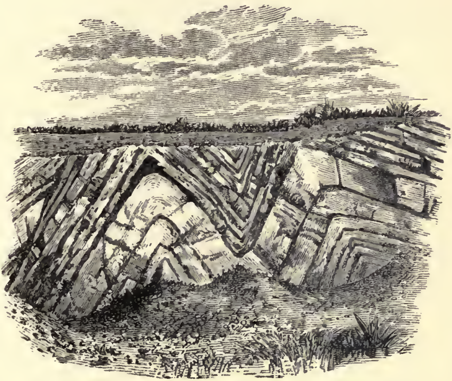


FIG. 47.—Curved limestone, Draughton, near Skipton.

that not only have the rocks of the earth's crust been folded in this equable and gentle way; but that they present proofs of much more intense movement. These may be looked for in the vicinity of faults, as has already been pointed out. Sudden and violent crumpling in the midst of comparatively undisturbed strata may be regarded as *primâ facie* indicative of the proximity of some dislocation. It will not, however, of itself be sufficient to prove the existence of a fault, for unexpected local twists and severe plication sometimes occur where, though the rocks must have been subjected to intense

FIG. 48.—Shales contorted by a landslip.

lateral compression, they have not actually been fractured. On a small scale, the most tumultuous contortion of soft strata may often be seen as the result of a landslip. In Fig. 48, for example, a set of dark shales lying under a thick sandstone have been crushed up by slips of the heavy overlying rock, yet the ruin has been so well concealed by vegetation that a careless observer might suppose the lower twisted beds to be much older than, and unconformably covered by, the upper horizontal strata.

There occur wide tracts of country where the underlying rocks have been so violently disturbed, that for miles they seem to be standing on end. In such cases, it is usual to find some one prevalent direction of strike along which the vertical or highly inclined beds range themselves. And a careful examination will generally disclose proofs that the strata really consist of many rapid folds, the same beds being repeated again and again. Sub-

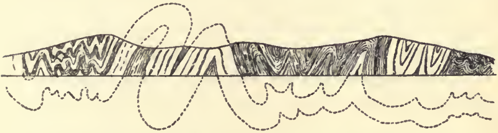


FIG. 49.—Section of what at the surface might be mistaken for a continuous highly inclined series of strata, shown to consist of numerous anticlinal and synclinal folds. Gneissose rocks, Loch Quoich, Inverness-shire.

sequent extensive denudation has worn away the tops of the arches and produced a form of surface which may have little or no reference to the structure of the rocks below (Fig. 49).

Rocks contorted in this way are pretty sure to present cases of *isoclinal* folds, that is, the axes of the curves are not vertical but inclined. In Fig. 50, for example, the folds are all inclined in the same direction, so that in each of them one half of the curve has its strata turned bottom uppermost. Inversions on a grand scale are to be seen in great mountain-chains like the Alps. The accompanying drawing (Fig. 51) represents a very remarkable example which occurs in the mass of the Glärnisch, one of the eastern Swiss Alps, as described by Dr.

FIG. 50.—Reflexed contortions or isoclinal folds.

Baltzer. The peak (Ruchen) reaches a height of 2107 metres above the valley to the left of it (Klönthal). The folded rocks belong to the Cretaceous system of the Alps.

Cleavage.—By the powerful lateral pressure to which rocks have been subjected during their subsidence and contortion, their minute particles, which usually present one axis longer than the others, have been compelled to adjust themselves in the rock along lines of least

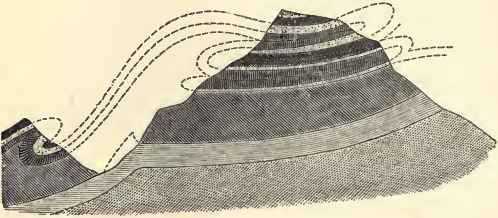


FIG. 51.—Section of the grand inversions of strata in the Glärnisch Mountain, Eastern Alps.

resistance; that is, with their longer axis perpendicular to the direction of the pressure. Mr. Sorby showed by ingenious experiments, that with suitable adjustments of pressure this re-arrangement could be imitated artificially in different substances, even in so homogeneous a body as wax poured in a melted state upon a surface of glass. Rocks in which the change has been superinduced are said to be *cleaved*, and the change itself is termed *cleavage*.

Considerable practice is required to distinguish between the fissile structure thus developed by cleavage, and that due to original lamination of deposit. Should the rock consist of alternate bands of different textures or colours, such alternation will of itself be sufficient to show the bedding; while a further test will be found in the frequent

FIG. 52.—Cleavage of curved strata, coinciding with the stratification at *b b*, but at a right angle to it at *a a*.

difference in the fineness of the cleavage as it passes from one rock into another. Fine-grained argillaceous rocks assume the most perfect cleavage; hence their value as slates. Their original bedding may be entirely effaced. Sandy and gritty rocks do not allow of the development of such fine divisional planes. Consequently the cleavage-lines may actually be seen to stop when they reach an arenaceous stratum (Fig. 53) and begin again on the further side at the next argillaceous band. Where no such intercalation of different strata can be observed, the geologist looks for lines of colour corresponding with original lamination. Should these fail, he may for an interval find it impossible to make sure in what direction the lines of stratification run. It will be perceived from

Fig. 52 that cleavage runs independent of original bedding, coinciding with it or not, as the strata may happen to lie. The strike of the cleavage, which can be traced with great persistence over large areas, as in North Wales, marks the direction perpendicular to which the compression of the rocks took place. In following it, therefore, the observer will keep a watch for every indication of other evidence as to the nature and extent of the

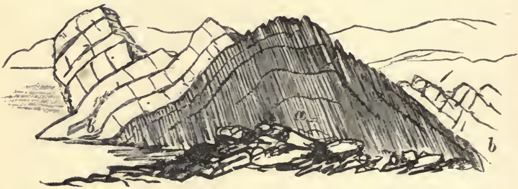


FIG. 53.—Deceptive appearance of unconformability due to variations in the effects of cleavage upon different materials. West coast of Islay.

terrestrial movements by which these great changes were effected.

In a cleaved region, the greatest risk of error which the observer encounters is the liability to mistake cleavage for bedding, and thus to form a false conception of the geological structure of the ground. He ought to be continually on his guard against this source of deception, which has misled even experienced geologists. Not only may erroneous conclusions be drawn as to the true inclination and thickness of cleaved rocks, but in some instances an unconformability may be supposed to exist in what is really a continuous succession of strata. This latter mistake may readily be made where a mass of well-cleaved slate is overlain by a coarse, pebbly grit or conglomerate, which has resisted the process of cleavage. In Fig. 53, for example, the slates (*a*) might at a first glance be mistaken for an older and entirely distinct group of rocks from the grits (*b*) overlying them. But further examination would probably disclose indications of lines of bedding running through the slates parallel with those of the grits above, as indicated in the diagram. Errors from this cause are so naturally made, but so misleading in their effects, that too much caution cannot be exercised to avoid them.

CHAPTER XII

IGNEOUS ROCKS

THE foregoing chapters have treated chiefly of the structure of the stratified rocks, although the same principles which guide us in dealing with them are also in great part applicable to the Igneous rocks. These latter, however, present some features of their own which mark them off in strong contrast with the former, and which the geologist can learn to distinguish only by actual practice in the field.

At the outset, the observer must be able to recognise an igneous rock when he meets with it. After some experience, he will, in the majority of cases, have no difficulty in this discrimination, provided he has made himself familiar with the characters of such rocks by handling specimens of them. But the carefully selected specimens of a museum or private collection do not always convey a correct idea of the external character of the rocks as they occur on the hill-side or ravine. It is specially needful that the hammer be vigorously plied during at least the earlier part of a geologist's study of igneous rocks. He will find them so constantly decayed at the surface, so thickly covered with a weathered crust, and, in many cases, so deeply corroded by the percolating water which has decomposed their silicates, that he may experience no little difficulty in procuring a tolerably fresh fracture from which to judge what the real character of the rock may be. The weathered surface, however, often helps in this discrimination, for the decay of the more decomposable minerals sometimes leaves the others more easily recognisable than in the unaltered state. Should the observer find himself at a loss how to name a rock, let him take one or two chips in his pocket, wrapping them in paper, with a label inside, to mark their proper locality. When he gets back to his quarters in the evening he may submit one or two minute splinters of the rock to blow-pipe tests (p. 214), or if these be inapplicable, or give no satisfactory results, he may proceed, in the manner described in later chapters, to reduce a fragment of the stone to powder (p. 227), or to prepare a slice of it for examination under the microscope (p. 228). If even after all these trials the rock still puzzles him, he had better give it some provisional name, and lose no more time over its determination, but proceed with his field-work, laying aside, however, some good typical specimens of the doubtful rock for subsequent more careful analysis either by himself or some experienced petrographer.

Having acquired more or less facility in detecting igneous rocks by their lithological characters, the observer may proceed to study their structures as rock-masses and the part they have played in the architecture of the earth's crust. He will find by practice that for the purposes of field-geology they are conveniently divisible into two great series—(1) the Crystalline, including granite, syenite, with all the once melted rocks like the lavas; and (2) the Fragmental (Pyroclastic), including the consolidated volcanic ashes, tuffs, and conglomerates. As a rule, these two series are broadly and distinctly marked off from each other, both by their lithological characters and by their behaviour as rock-masses.

The Crystalline igneous rocks, as their name indicates, have solidified from molten or from aquo-igneous solutions; sometimes remaining still in the condition of glass, sometimes completely crystalline, and with every possible gradation between these two extremes. But though for the most part recognisably crystalline in the field, they are not always so. Many ancient eruptive rocks, for example, might in hand-specimens be taken for pieces of hardened clay. In such cases, should the lithological characters be indefinite, the true character of the rock may usually be ascertained from its relation to the surrounding masses. If these are obscured, the final appeal may be to the microscope. Hence the learner must be prepared for endless varieties of texture, colour, hardness and softness, toughness and friableness, among the once molten igneous rocks.

The Fragmental series is less varied, as its members consist of fragmentary materials, derived partly from the explosion of lava rising in the throats of volcanoes, and partly from the *débris* torn from the sides of the volcanic funnels and craters. These rocks are essentially characterised by the fragmental nature of their component particles, which may vary in texture from the finest impalpable dust up to blocks weighing many tons. Considerable variety must obviously exist in the coarseness or fineness of the consolidated masses. They may pass on the one hand, by admixture of ordinary sediment, into sandstones and shales; on the other, into the coarse tumultuous agglomerate of purely volcanic origin, so commonly found filling up former vents of eruption.

Igneous rocks may be conveniently classed as Plutonic, or deep-seated, when they have solidified deep within the crust, and as Volcanic, when they have been erupted or at or near to the surface. Fundamentally, however,

FIG. 54.—Section of a portion of the earth's crust broken by two dislocations whereby three different masses of stratified rock, A, B, and C, have been brought into juxtaposition, and with two masses of intrusive igneous rock I, which have risen along the lines of fracture.

they are all parts of one great series. In the more superficial or volcanic group they may either be intrusive or interstratified; that is, they may either have been intruded among the rocks with which they are associated, or they may have been poured out at the surface in sheets, which in a great continuous series of deposits thus come to be interbedded between the strata below and those above them.

It is of course evident that as these crystalline masses have all risen from molten reservoirs within the earth, they were all originally intrusive in the earlier or deeper part of their course. Every interstratified sheet must have been connected somewhere underneath with the intrusive pipe or vein by which it rose to the surface, although the connection may have been subsequently destroyed or concealed. An intrusive mass, on the other hand, may never have been connected with the surface at all. Interstratified igneous rocks prove the former existence of active volcanic vents at or near the localities in which they occur. Intrusive igneous rocks may be due to ancient deep-seated movements in the crust of the earth, which never gave rise to any of those surface manifestations usually held to be expressed by the term volcanic. An accurate discrimination between these two groups is of importance when the history of a volcanic district has to be made out. The field-geologist should especially bear in mind the following leading characters of each of the groups.

1. **Intrusive Rocks** may occur in the form of (1) Veins (Figs. 55, 58, 63), traversing at any angle the rocks among which they rise, (2) Vertical wall-like masses or Dykes, (3) Irregularly circular masses forming the upper ends of vertical columns or pipes called "Necks" (Figs. 59, 60, 61), (4) Injected Beds, Sheets, or Sills (Figs. 55, 56), or (5) Irregular amorphous Bosses (Fig. 62).

When an eruptive rock can be seen to intersect any of the beds of a series of strata, its intrusive character becomes at once apparent. But when it lies between stratified rocks, and assumes the form of a bed, some care is needed to make its intrusive character certain, for it might then be taken for an interstratified sheet. It is usually characterised by being much closer in grain near its junction with the other rocks than in the central parts of its mass (Fig. 57). This "chilled edge" not only serves to distinguish an intrusive from a contemporaneously interstratified sheet of igneous material, but may be used to determine the relative age of intrusive masses which are associated together. Where one of these masses presents a chilled edge to another mass it may be inferred to be the younger of the two. Again, the rocks lying upon an intrusive rock may be hardened, and sometimes exceedingly altered, while detached portions of

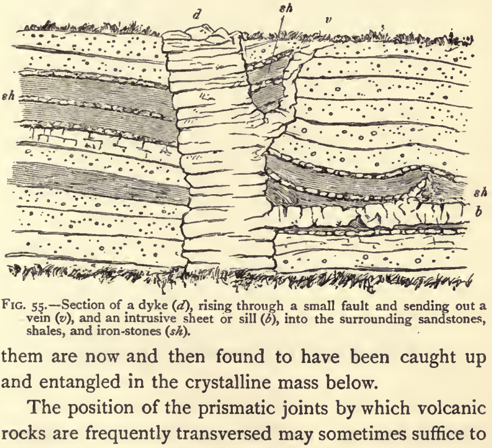


FIG. 55.—Section of a dyke (*d*), rising through a small fault and sending out a vein (*v*), and an intrusive sheet or sill (*b*), into the surrounding sandstones, shales, and iron-stones (*sh*).

them are now and then found to have been caught up and entangled in the crystalline mass below.

The position of the prismatic joints by which volcanic rocks are frequently transversed may sometimes suffice to indicate whether a rock is certainly intrusive or possibly interstratified. These joints start from the cooling surfaces of the original melted mass of lava. In a bed they are of course perpendicular to its upper and under surfaces; in a dyke or vein they vary according to the inclination of the mass, being horizontal when the dyke is vertical (Fig. 55).

When an igneous rock has been cut through by a fault, the fractured surface, especially when rough and shattered,

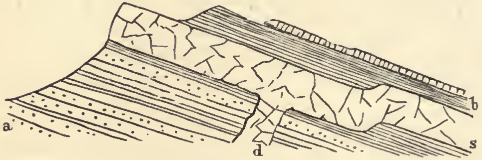


FIG. 56.—Section of intrusive sheet or sill (*s*), underlying strata (*b*), and overlying the group (*a*), and connected with a dyke or pipe (*d*).

may assume a deceptive resemblance to the original wall of a truly intrusive mass. But in such a case it would probably be found that the surfaces both of the igneous rock and of those next it showed, in their striated and polished appearance, evidence of having been made to grind against each other as solid masses (slickensides).

Dykes vary in thickness from less than an inch to 100 feet or more, and from a vertical to a more or less

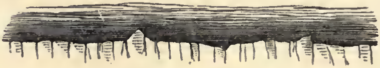


FIG. 57.—Upper surface of an intrusive igneous sheet or sill with overlying shale.

inclined position. They often rise along previous lines of fracture; but in the great majority of cases the basalt-dykes of Tertiary date, so abundant in Britain, have filled fissures without any perceptible vertical throw of the rocks on either side. Sometimes a dyke may be found, as in Fig. 55, to send out ramifications, though this is not so common as might be supposed. In some volcanic districts, the molten material has been injected into innumer-

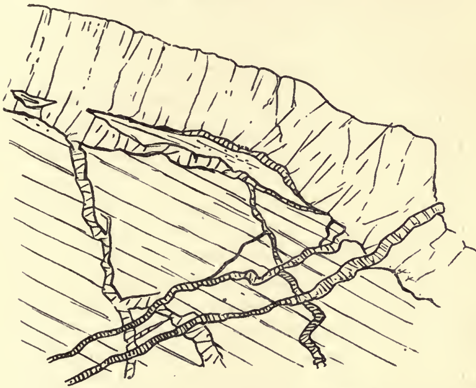


FIG. 58.—Basaltic Veins traversing Jurassic, Ardnamurchan rocks, Argyllshire.

able irregular rents, and has consolidated there as Veins. The rocks underlying the Tertiary Volcanic plateaux of Britain present hundreds of striking illustrations (Fig. 58).

The amount of alteration on the surrounding rock produced by dykes is usually surprisingly small. Sandstone is hardened into a kind of quartzite, and occasionally even acquires a columnar structure, the prisms being directed outwards from the sides of the dyke. But the alteration seldom reaches beyond a few feet. Shales suffer more, as they are found baked into a kind of porcelain-jasper; but this may frequently be observed not to extend further than an inch or two into the rock; while along many dykes the shales show scarcely any perceptible hardening. It is where they come in contact with carbonaceous shales, or still more with seams of coal, that dykes and intrusive sheets produce their most marked metamorphism. The coal has sometimes been entirely consumed, and a layer of igneous rock has taken its place. At other times a thin sheet of molten lava has been injected along the top, bottom, or centre of the coal-seam, converting it into a kind of anthracite or into a mere cinder. Examples may be found where the coal has been fused into a cellular mass, and has subsequently had its vesicles filled up with infiltrated carbonate of lime. In Ayrshire numerous beautiful sections have been laid bare, where the coal has been rendered prismatic, the hexagonal or polygonal prisms, like so many bundles of pencils, diverging from the surface of the intruded igneous rock. At the same time, it is where they have inflicted such injury upon coals and carbonaceous shales that the igneous masses have themselves experienced most alteration. The most solid black crystalline basalt, where it runs through one of these strata, is changed into a pale dull yellow or white clay, so deceptively like some of the fire-clays of the coal-fields that it will hardly be admitted by most observers to be anything else until they trace out its relations. But they may find it passing insensibly into the ordinary condition of basalt or diabase, as it recedes from the carbonaceous bed the combustion of which has reduced its oxides. A thin section of one of these "white traps," placed under the microscope, still shows traces of the original crystalline structure of the mass, but with the component minerals entirely altered.

It would seem that, as a rule, the extent of alteration in the rocks adjoining an intrusive igneous mass bears

FIG. 59.—Outline of a Volcanic Neck.

some proportion to the size of the latter. We may be prepared for traces of the change at a greater distance from a large injected sheet than from a small dyke.

The "Necks" which mark the sites of former volcanic funnels commonly form rounded or conical hills (Fig. 59). They consist sometimes of crystalline rocks, sometimes of tuff or coarse agglomerate. These materials

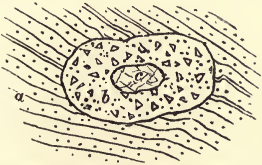


FIG. 60.—Ground-plan of the structure of the Neck shown in Fig. 59.

descend, of course, vertically through the surrounding rocks, which are sometimes considerably altered all round (Fig. 60). Necks vary in size from a few yards to a mile or more in diameter. Many interesting examples have been mapped in the course of the Geological Survey of Scotland, in the Old Red Sandstone, Carboniferous, and Permian system.

The deep-seated or plutonic rocks frequently occur as Bosses. Granite and other massive rocks usually assume this form. They include no true fragmental series, nor have they any cellular, scoriform portions, for these could only be formed towards the surface, where by relief from pressure, the imprisoned steam had liberty to expand and push aside the particles of the still fluid rock.

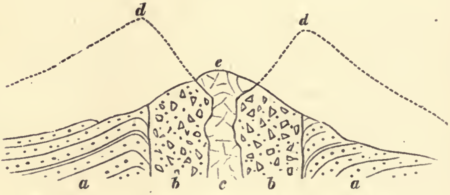


FIG. 61.—Section through the same Neck as in Figs. 59 and 60.

Having cooled slowly under great pressure, they are often highly crystalline. They occur as huge amorphous masses, sometimes seventy miles long, as in the granite of the south-east of Ireland. They also assume the form of veins and dykes, often ramifying in the most complex way through the rocks which they traverse. A ring or "aureole" of metamorphism is usually to be recognised round large eruptive bosses of plutonic rocks. Within this ring, which may vary from a few yards to a mile or more in breadth, a series of interesting mineralogical reconstructions may be found, and gradations may be traced from ordinary sedimentary strata through increasing stages of induration and re-crystallisation, until

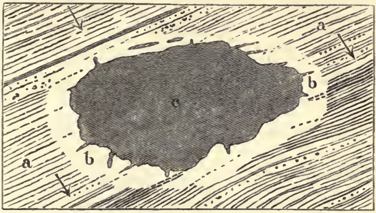


FIG. 62.—Ground-plan of Granite-boss with ring of Contact-Metamorphism; (*a*) sandstones, shales, etc., dipping at high angles in the direction of the arrows; (*b*) zone or ring within which these rocks are metamorphosed; (*c*) granite sending out veins into *b*.

we reach such rocks as chiastolite-slate and even entirely crystalline mica-schist.

These features can be well studied round the flanks of a large mass of granite (Fig. 62). A network of veins

FIG. 63.—Granite veins, Cornwall. (De la Beche.)

may sometimes be seen proceeding from the granite, intersecting each other and inclosing portions of the surrounding rock (Fig. 63). The veins vary from a breadth of many yards down to the merest thread. A marked variation in lithological character may be observed as a rule to attend these changes in the dimensions of the veins. The larger veins may consist of a crystalline rock, like that of the main mass; but as they ramify and diminish they pass into an elvanite (microgranite) or fine-grained felsite.

2. **Interstratified igneous rocks** are sheets of volcanic material which have been ejected at the surface and have solidified there. Consequently, whenever they can be satisfactorily determined, they show the former existence of volcanic activity on or near to their site. The geological date of their eruption can be ascertained by an examination of the strata with which they have been contemporaneously associated. Thus, for instance, if we find a set of lavas and tuffs interstratified with limestones and shales containing *Productus giganteus*, *Lingula squamiformis*, *Athyris ambigua*, *Lithostrotion junceum*, etc., we conclude without hesitation that as these are unequivocally Carboniferous Limestone fossils, the volcanic eruptions must have taken place during the period of the Carboniferous Limestone (Fig. 64).

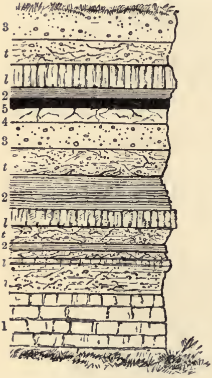


FIG. 64.—Section of interstratified igneous rocks, Linlithgowshire. *l*, *l*, lavas; *t*, *t*, tuffs; 1, limestone with marine organisms (Carboniferous Limestone); 2, shale; 3, sandstone; 4, fireclay; 5, coal.

It is obviously important, therefore, to be able to determine satisfactorily whether igneous rocks have been contemporaneously poured out during the deposition of the formation in which they occur, or have been injected into that formation after its accumulation. The existence of unmistakable beds of tuff (*t*, *t*, Fig. 64) would settle

FIG. 65.—View of the Island of Staffa and Fingal's Cave, showing amorphous and columnar basalt resting upon tuff.

the question. These rocks consist of ejected volcanic detritus, and must have been laid down at the surface; they could not be injected as in the case of crystalline rocks.[1] Whenever, therefore, we encounter interstratifications of volcanic tuff in a group of sedimentary formations, we are justified in regarding them as evidence of contemporaneous volcanic activity. The observer should

[1] Exceptional cases occur where the tuff that fills a volcanic vent has found its way into cracks in the walls of the funnel.

study carefully a good series of specimens of various tuffs from different geological formations, and learn to distinguish them from mere mechanical detritus derived from the superficial disintegration of igneous rocks.

But the proof of former volcanic action is vastly strengthened when we find not only the consolidated ashes, but also the lava-streams of the period (*l*, *l*, Fig. 64). A truly interstratified sheet of crystalline rock is, in fact, a lava-stream which has been poured out at the surface, either on land or under water, and shows the distinctive characters of such a bed. Thus it is commonly

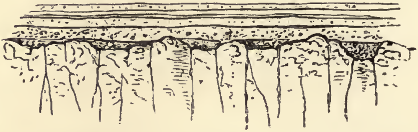


FIG. 66.—Upper surface of an interstratified igneous sheet with sedimentary strata lying upon it.

rough and slag-like towards its top (Fig. 66) and bottom, and most compact about the centre. The strata lying upon it, having been deposited there after the emission of the lava, are not altered, have no portions of their substance entangled in the crystalline rock, but, on the contrary, may contain detached fragments of the latter.

It is eminently characteristic of lava to acquire a cellular texture, from the expansion of the abundant steam imprisoned within it at the time of eruption. This feature is specially developed at the top where, the pressure being least, the vapour has had most freedom of motion. As the vesicles appeared while the rock continued to move, they may frequently be observed to be pulled out into oval or almond (*amygdaloidal*) shapes in the direction of the motion (Fig. 68). Indications of this kind mark the flow of lavas in all geological periods, and should always be noted when they occur, for they may help to show from what quarter the lava came, and where therefore the vent of emission should be looked for.

During their cooling and contraction, sheets of lava acquire a jointed structure, such as has already been referred to. The chief set of joints usually starts from the

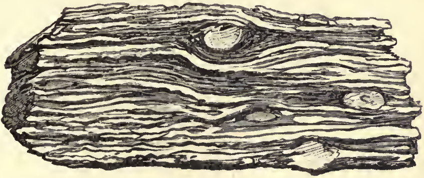


FIG. 67.—Flow-structure in a nodular Upper Silurian rhyolite, Clogher Head, Dingle, natural size.

cooling surfaces, that is from the top and bottom of the sheets; but other systems of "fissures of retreat" may be developed more or less at right angles to these, so that the lava is divided into vertical masses, which may be further cut into segments. The most perfect joint-structure is that known as the columnar or basaltic, where a rock is built up of slender pillars, having five, six, or an irregular number of sides. This structure is conspicuous in many basalt-sills among the Western Isles of Scotland. Sometimes the pillars are long and parallel as in the columnar part of Staffa (Fig. 65); in other cases they are short, narrow, curved, irregular and starch-like as in the upper basalt that overlies the columnar sheet in Staffa.

Many ancient as well as modern lavas exhibit what is called a "flow-structure," due to the irregular devitrification and consolidation of the mass while still in motion. (Fig. 67). This streaky structure sometimes shows remarkable corrugation, indicating how the partially

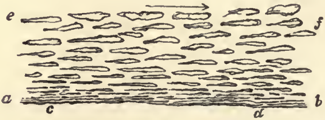


FIG. 68.—Steam-holes in lava drawn out in the direction of the flow of the mass (*e f*) and becoming more and more flattened till on the line *a b* they are compressed into mere streaks and give a fissile structure to the rock.

solidified layers were driven onward by the motion of the general body of the lava. By attending to the direction towards which these layers have been pushed, we may now and then obtain satisfactory evidence as to the quarter from which the streams of molten rock proceeded.

The upper part of a lava stream still in motion is often a confused heap of rough blocks of slag, among which rents appear opening down into the still red-hot mass underneath. Many of these rents remain unclosed when the lava comes to rest. If we imagine such a cracked sheet of rock to have sand or mud laid over its surface, the cracks would be filled up first, and if the sand were brought in gradually, there might be time for it to arrange itself in a stratified manner between the walls of the fissures. No better evidence could be given that the lava must have been poured out at the surface, and not injected as an intrusive sheet. Evidence of this nature abounds among the volcanic rocks of the Lower Old Red Sandstone of Scotland (Fig. 69). In these

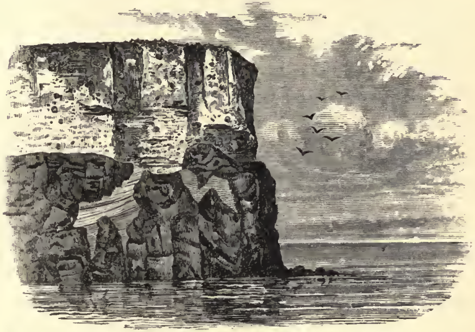


FIG. 69.—Cracks in an Old Red Sandstone lava which have been filled in with sandstone from above, Coast of Kincardineshire.

examples, the discharge of the lava was succeeded by a period of volcanic quiescence, during which ordinary sediment was strewn over the bottom of the water. Sometimes the lava-beds in an old geological formation are succeeded by beds of volcanic tuff, or these two kinds of rock are intercalated with each other in such a way as to show that streams of lava and showers of dust and stones must have been erupted too rapidly to permit of the accumulation of any prominent beds of ordinary sediment between them. The way in which lavas and tuffs sometimes alternate in a series of ancient strata is well illustrated in Fig. 64, which represents the characteristic grouping of volcanic and sedimentary materials in the Carboniferous Limestone series of central Scotland. In the diagram, Fig. 28, the series of rocks marked *P* in the southern part of the map are examples of interbedded lavas and tuffs. They occur under circumstances very similar to those of ordinary stratified rocks. They dip one below the other in orderly succession, and are traversed by faults, like the beds of sandstone and conglomerate which lie below, between, and above them. In an actual volcanic cone, where only volcanic materials occur, a more complex arrangement is found. Lavas and tuffs there succeed each other in rapid alternations, often cut by dykes or veins. Volcanic cones belonging to old geological periods have seldom been preserved, for they would usually be washed down by the waters of the seas or lakes in which they sank. It is not uncommon, however, to meet with the "necks" above described (Figs. 59, 60, 61), which may be regarded as the roots or stumps of cones from which the overlying pile of ejected materials has been worn away by denudation (*V V* in Fig. 28). This lower or downward prolongation of the original cone, as I have already mentioned, may consist either of masses of lava or other crystalline rock, or of consolidated fragmentary materials. In the latter case the tuff or agglomerate has sometimes become itself crystalline, owing, no doubt, to the long continued upward passage of steam, hot vapours, and gases through the volcanic vent after the explosions ceased.

As illustrations of the way in which the structure of a volcanic region is worked out and expressed upon a map, I may refer to the Sheets of the Geological Survey of England and Wales, particularly 75 and 78, embracing the Snowdon region; and to Sheets 22, 23, 32, 33, 39, 40, and 41 of the Geological Survey of Scotland, showing the development of the volcanoes of the Old Red Sandstone, Carboniferous, and Permian periods in the midland districts of Scotland.[1]

[1] The subject of this chapter will be found more fully discussed in my *Ancient Volcanoes of Great Britain*, 2 vols. 1897.

CHAPTER XIII

SCHISTOSE ROCKS—MINERAL VEINS

A GEOLOGIST who, with some little experience of stratified and igneous rocks, finds himself for the first time in a region of crystalline schists, meets on every hand with phenomena, which, though he may be familiar enough with the descriptions of them in books, cannot but strike him as strangely anomalous when he comes actually face to face with them in nature. The rocks are manifestly crystalline, and in small fragments or hand-specimens may often recall some of the igneous rocks with which he may already be acquainted. But when looked at in mass, they have an arrangement of their component minerals such as he probably never observed in any igneous rock. The felspars, hornblende, quartz, mica, and other constituent minerals, are disposed in more or less regular wavy lines, and the rock splits along these lines more readily than in other directions. Again, so distinct sometimes are the parallel seams of different mineral composition, that the rocks might at first be mistaken for ordinary sedimentary strata. Yet a little further examination shows that the layers or folia are welded or felted into each other by the interweaving of their crystalline constituents, that they are usually very inconstant, that they are apt to thicken out capriciously into concretions and thin away rapidly, and that they often possess a curious puckered or crumpled character, which can be seen in large contortions on the face of a mountain, and descends even into such minute forms as can only be observed with a microscope. It is evident that rocks presenting such remarkable characters must offer many points of difficulty as well as of interest to the field-geologist.

In beginning the examination of a region of foliated rocks, the observer may of course dismiss from his mind the idea of receiving help from organic remains. In rare instances, indeed, traces of fossils have been obtained from schistose rocks, or from altered limestones associated with these rocks. But this is an accident not to be counted upon. With the absence of palæontological assistance, there is also a great lack of stratigraphical aids, so that the learner may be led, after a few efforts, to give up as hopelessly impracticable the task of making out any structure of the ground. Yet he will be surprised in the end at what can be done by patient observation of the puzzling masses. He may be led to collect their minerals, and if so, will find them in many places, particularly among the limestones, to be a rich storehouse of beautiful and interesting varieties. By degrees he will discover that particular rocks are distinguishable by special minerals, and he may even be able to trace such rocks or bands of rock across the mountains by means of these peculiar minerals, which will thus be put to the same kind of use as fossils are by the stratigrapher.

Gradually the idea of following the same band among the contorted masses of the schistose rocks will seem to him more and more feasible; and he may at length be induced seriously to make the attempt to unravel the complicated geological structure of the region.

In these investigations I have found that four points deserve to be kept steadily in view. (1) The nature and distribution of the minerals. (2) The varieties and alternations of the rocks. (3) The direction of the prevalent foliation, and whether or not it coincides with bedding. (4) The evidence of crushing, and the existence of thrust-planes.

1. As I have just said, the minerals for which regions of gneiss and schist are celebrated may be employed by the stratigraphical geologist much as he would use fossils. Besides their own beauty, they afford endless interest and instruction in the light they cast upon the formation of the rocks among which they occur, and in the problems they present to us regarding mineral growth. But these aspects must be studied chiefly in the laboratory, and with the microscope. In field-geology, the observer notes as many facts as strike his mind in connection with theoretical speculation, but for his own work at the time it is the association and distribution of the minerals which are of prime importance. He will therefore watch, as he traverses the mountains, under what circumstances special minerals occur. Let us suppose for example, that he encounters a rock containing the beautiful bluish-grey mineral called kyanite. He carefully notes how it occurs, with what other minerals associated, and in what kind of rock. Wherever he comes upon a loose fragment of

the mineral he tries to find it *in situ*, and if successful, compares the new habitat with those previously observed. Let us further assume that he discovers it always to lie in the same long-bladed plates or prisms, with the same associated group of minerals, and in the same or a similar kind of rock. This fact established would be one of high importance in any attempt to work out the geological structure of the district. Massive hornblende, actinolite, garnets, chlorite, and different micas may all be found to characterise particular bands of rock. In many wide regions, however, no such special mineral zones are to be seen. The rocks present a singular monotony of character, or their abundant minerals are not confined to special horizons, so that if their order is to be determined, it must be done by some other method than that furnished by mineral evidence.

2. But where the rocks furnish no specially prominent mineral zones, they often present in themselves great varieties of composition, structure, and texture. The observer will duly note these characters with the view of ascertaining whether he has to deal with true Archæan masses or with a younger series of altered sedimentary formations. He discovers, let us suppose, a coarse-grained mass of gneiss with large crystals of pink orthoclase—so peculiar a rock that even small fragments can readily be recognised. After noting its lithological characters, he proceeds to investigate its surroundings. He finds that though, looked at in hand-specimens, it seems structureless, like a coarsely crystallised granite, yet that a distinct foliated structure exists throughout its mass, and that parallel with this foliation there occur, on either

side, bands of a different composition, such as folia of hornblende and quartz, or of felspar and mica, or of some other combination of the same or other minerals, sufficient to mark off these bands from the gneiss. Hence the gneiss itself is a thick bed or bed-like mass,

FIG. 70.—Crumpling and thrust-planes in gneiss—south coast of Mull.

and its continuation must be traced along, and not across, the line of foliation.

Among Archæan rocks no such regularity of outcrops is met with as we find among stratified formations. But broad bands of rock, differing from each other in mineral characters, may be recognised and traced. Sometimes we encounter a zone of grey gneiss with perhaps little or no mica; then may come another zone abounding in black mica or in hornblende. A third tract may be characterised by the prominence of its pink pegmatite bands; a fourth, by the number of its dark basic dykes; a fifth, by its inconstant beds and lenticles of limestone or graphitic schist.

But it has seldom been found possible to determine any satisfactory order of succession among these rocks, or to be sure that what seems to be such an order has really any chronological significance. The observer will soon discover proofs of intense disturbance among these masses. He will find them crushed, fractured, crumpled, and pushed over each other by thrust-planes, and he may be driven to conclude that the divisional planes, though here and there they may simulate bedding, may be entirely due to some other cause. He will not infrequently be led at last to regard a whole series of gneisses as originally a complex mass of eruptive rocks of different ages which have been injected through each other, and have subsequently been crushed and sheared. In such circumstances, probably all that he can hope to establish will be the order of appearance of the various materials. It may be possible to discover, from the evidence of intrusive veins, which portions of the series are newest. Sometimes, where no such veins are available, the close-grained or "chilled" edge, which betokens the contact of an injected mass with a cooler and older rock, may have in some measure survived the general metamorphism, and be still traceable (see p. 161). Much assistance in an investigation of this kind may be derived from a study of the structure of a Palæozoic or even Tertiary core of eruptive material, consisting of a complex series of successive intrusions.

On the other hand, where the schists have been produced by the metamorphism of an original sedimentary series, they may reproduce some of the more characteristic structural features of stratified rocks. A definite order of succession may be made out among them; and their groups of quartzite, limestone, pebbly grit, phyllite, mica-schist, hornblende-schist, epidiorite and other rocks may be traceable continuously for long distances.

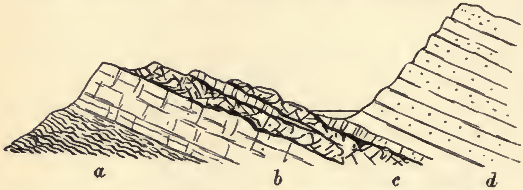


FIG. 71.—Limestone intercalated among schists and quartzites—Lough Salt, Donegal. *a*, silvery mica-schist; *b*, limestone and dolomite; *c*, epidiorite (probably originally intrusive basic igneous rock) crushed in places into hornblende-schist; *d*, quartzite.

Bands of limestone and dolomite are particularly valuable as guides in unravelling the structure of a schistose country. Their line of outcrop can frequently be followed, even from a distance, by the tract of brighter green herbage, supported by the richer calcareous soil which they yield, and contrasting sometimes strongly with the brown moorland on either side. In a cultivated region, especially where the surface is obscured by superficial accumulations, quarries may often be found in the limestone, admitting of an inspection of its character and mineral contents. Limestone bands, moreover, among schistose, as among ordinary sedimentary strata, are not infrequently distinguished by their continuity. A belt of limestone has been traced through the heart of the schistose rocks of the Scottish Highlands for a distance of 200 miles, and similar (probably the same) rocks are prolonged into the west of Ireland—a distance of more than 200 miles farther (Fig. 71).

Each district must be judged of by itself, and according to its local peculiarities will be the choice of zones by the geologist. He will endeavour to ascertain in what order the different varieties of rock appear to succeed each other, whether or not, in any continuous section, he can determine a true chronological order of succession among them, and whether, if such an order can be made out in one place, it can be extended to others.

3. Apart from the constant variations in the lithological nature of the rocks, it is desirable to note the character and strike of the foliation. Over large tracts of the Highlands of Scotland, the direction of the foliation of the schists is as persistent, constant, and easily traced as the strike of any series of sedimentary formations.

In some regions, there can be no doubt that the foliation coincides on the whole with the original bedding. If, for example, we find that, parallel with the planes of foliation, bands of totally distinct mineral character alternate with each other, such as phyllite, quartzite, schistose conglomerate, and crystalline limestone, we may with some confidence infer that these bands, though now more or less crystalline and schistose, represent original distinct bands of sedimentary material. In many districts, though we may be tolerably certain that the rocks are metamorphosed sediments; yet we may lose all reliable evidence of their bedding and consequently of their order of succession, and then the foliation-planes, no matter how distinct and persistent, can afford no trustworthy clue to the original sequence and structure of the schists. In other areas the structure of the rocks is so entirely crystalline, and the absence of any sign of sedimentary origin in the rocks is so complete, that we must seek for some other explanation of their banded structure than that which would account for it by regarding it as bedding.

Foliated rocks are commonly crumpled and puckered on a minute scale, as well as plicated on a large scale. Sometimes they appear to be ranged vertically, like books in a library. But a broad tract of bedded rocks set on end, must often mean, as we have already seen, that they have been folded upon themselves, and that the tops of the folds have been cut away. (See p. 151, Fig. 49). In fact, they may be so rapidly and constantly repeated, that though placed on end, a comparatively small thickness of strata may be made to cover a wide space, and thus an effect may be produced somewhat like that which would arise if they were approximately horizontal.

If it is difficult to follow out the structure of a crumpled region of ordinary sedimentary rocks, it is tenfold more arduous to make progress in one of the crystalline schists. The observer, however, may do much by making numerous and careful observations of the direction and angle of dip, where he finds that the folia are not vertical, and has reason to suspect that they mark original bedding. In this way, he may detect lines of anticlinal and synclinal axes, and if he be fortunate enough to meet with any recognisable bands among the rocks, he may, by tracing them in their successive outcrops on different sides of these axes, succeed in deciphering the geological structure of the area.

4. Within the last few years much light has been shed upon the structure and origin of schistose rocks. Evidence has rapidly accumulated that these masses have

FIG. 72.—Schistose Conglomerate. Three miles S.W. of Westport, Mayo. Some of the blocks of quartzite are two feet long, and the matrix is a true schist.

been subjected to enormous pressure and extensive deformation within the earth's crust. The effects of the severe stresses which have affected them, are specially well marked in those rocks wherein the original structure can still be easily recognised. Among the schists, for example, there sometimes occur pebbly zones or bands of conglomerate, or even coarse boulder-beds. About the original water-worn and sedimentary nature of these materials there is generally no room for doubt. But on examination, it is found that the pebbles in the conglomerates have often been crushed, flattened, and even pulled out of shape, while the original sandy or gravelly matrix has become a crystalline schist (Fig. 72). But that is not all. We may observe that the pebbles have been pulled round in one general direction (Fig. 73), and that this direction is that of the foliation. From

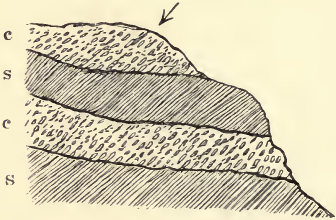


FIG. 73.—Beds of conglomerate and schist. Shore, Catacol, Isle of Arran. The pebbles in the conglomerate (*c*) have been moved round and placed with their longer axes in the plane of foliation (indicated by the arrow) which is oblique to the bedding of the schists (*s*).

such structures the conclusion must obviously be drawn that the rocks have been subjected to enormous lateral pressure,—that their component materials, as in cleavage, have been forced to rearrange themselves perpendicular to the direction of the pressure, and that a crystallisation of the crushed material has taken place along the planes of shearing or cleavage, which has resulted in the production of the foliated structure.

But it is not only in sedimentary rocks that this remarkable transformation may be seen. If the observer will carefully examine the undoubted igneous masses which have been intruded among schistose rocks, he will in many places be able to trace a complete passage from an unmistakable massive eruptive rock into the most typical schist. Coarse pegmatites, when they have come within the influence of the same shearing movements, have been crushed down into fragments, which may be traced getting smaller as they recede from the main body,

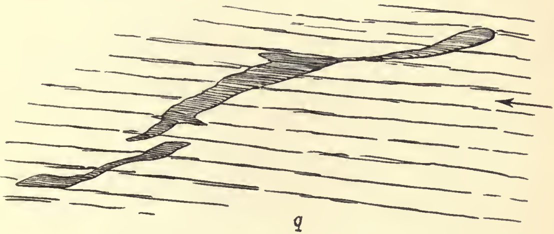


FIG. 74.—Dyke changed into hornblende-schist, near Dunfanaghy, County Donegal. The foliation of the schist runs obliquely across the dyke, and traverses also the surrounding quartzite (*q*) in the direction of the arrow.

until they disappear in a finely streaked felsitic substance (which might readily be mistaken for a rhyolite), or in a lustrous micaceous schist. Dykes of dark basic rocks, originally, no doubt, pyroxenic, have been changed into fissile hornblende-schists. Their central parts, where the dykes are broad, may still retain the original massive structure, or may present a series of cores preserving that structure inside, but passing externally into schist; while the marginal portions may pass into the most completely schistose condition. In the example shown in

Fig. 74 the whole of a narrow dyke has been rendered schistose, while here and there it has been attenuated or even ruptured along a plane of more intense movement.

It is thus evident that between cleavage and foliation an intimate connection can be traced. Cleavage may be regarded as the initial stage of the process, which when completed results in a mineralogical transformation

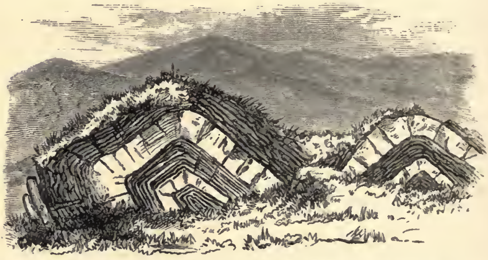


FIG. 75.—Foliation of mica-schist and grit-bands coincident with bedding; rocks subsequently folded.

and re-crystallisation of the constituents of a rock along certain planes known as planes of foliation. But it is conceivable that foliation may have been superinduced in planes which were not those of cleavage, or at least, which were older than the later cleavage. Among metamorphosed sedimentary rocks, it can sometimes be demonstrated that the planes of foliation coincide with those of bedding. The same coincidence often occurs, of course, between bedding and cleavage. But even where foliation has taken place along planes of original deposition, there may quite well have been considerable mechanical movement along those planes.

Just as cleavage does not always efface the original bedding of stratified rocks, so foliation sometimes leaves an earlier structure still traceable. Some ancient gneisses, for example, have undergone a second process of crystalline rearrangement in connection with mechanical compression and deformation, and reveal their older foliation not quite effaced by the newer.

No more profitable task can be undertaken by a geologist anxious to study the difficult problems of regional metamorphism, than the careful investigation of a district where the stratified rocks have been crumpled, cleaved, and dislocated, but where their original sedimentary characters still remain distinct. He can there make himself familiar with details of structure which, in the processes of mineralisation embraced in metamorphism, gradually become effaced. Thus the structure of the cleaved *killas* or slate of Cornwall is precisely similar to that of the schists of south-western Argyllshire. Only in the latter region, mineralisation has already set in, and the sediments have become partly crystalline. By successive stages, the crystalline re-arrangement becomes more developed, as the strata are followed further into the Highlands, until the original sediments can no longer be recognised in mica-schists and gneisses.

MINERAL VEINS

In connection with the schistose rocks I may refer to Mineral Veins which so often traverse these masses, though also found abundantly among stratified and igneous formations. Like lines of fault, with which indeed they often coincide, mineral veins, that is, veins filled with segregated minerals of various kinds different

Fig. 76.—Map of part of the mining district of Gwennap, Cornwall, *aa*, granite; *cc*, the surrounding schistose rocks; *bb*, elvan dykes; *s*, "greenstone"; *vv* and *dd*, two sets of metalliferous veins, or lodes and cross-courses (De la Beche's *Geological Observer*, p. 566).

from the surrounding rock, do not in the majority of cases attract attention at the surface. Their existence must usually be determined from other evidence than actual visible sections of them. If the geologist is at work in a district where veins of this kind occur, he should endeavour as early as possible to make himself familiar with the characteristic mineral substances which may constitute the chief part of the veins. Such minerals as quartz, barytes, calcite, and other "vein stones," as they are called, are of common occurrence, but often exhibit local peculiarities by which they may be recognised and traced to their sources. Having ex-

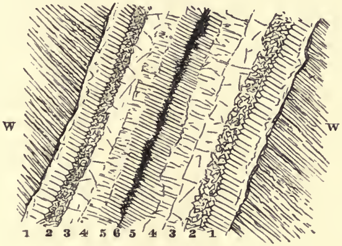


Fig. 77.—Section of a mineral vein.

amined sections of some of the mineral veins, and learnt the way in which the veinstones are associated with any metalliferous ore, the observer may be on the watch for evidence of the occurrence of the veins elsewhere. He follows with this view the same plan as that which I have already described with reference to the tracing of the limits of formations by means of scattered surface fragments (*ante*, p. 92). In ascending a stream or a hillside, he takes note of any marked number of pieces of veinstone, and of the point beyond which they grow fewer or cease. Having thus got a rough indication of the existence of one or more veins, he proceeds to a more minute search over that part of the ground, and unless the rocks should be too much concealed, he may hope to meet with an indication of the actual outcrop of the vein. It is not always, nor perhaps often, safe to pronounce as to the commercial value of such a vein from surface evidence of this kind. The rock may need to be opened up, and boring or mining may be required for some way below the surface before a reliable opinion can be expressed as to whether or not the vein may be workable to profit.

Mineral veins commonly run in straight or slightly bent lines, and often may be grouped in two or more series, one of which is usually cut by the others, forming thus a network of main-veins and cross-veins. The disposition of these veins may be inferred from the accompanying map of a portion of one of the mineral tracts of Cornwall (Fig. 76). The metalliferous character of a vein is apt to vary with the nature of the rock; plenty of ore may be obtained so long as the vein runs in one rock, but the supply is apt to diminish, or even to die out altogether in another rock.

As mineral veins have been filled in by the deposition of different minerals on the walls of fissures, a succession of deposits may be observed in their component materials. It not unfrequently happens that these deposits are in duplicate, the one half of the vein being a repetition of the zones of the other half. In Fig 77 for instance, the original walls (WW) of the open fissure are each coated with a layer of quartz (1, 1). Then comes one of blende (2, 2), another of galena (3, 3), a fourth of barytes (4, 4) and a fifth of quartz (5, 5). The centre (6) is sometimes left empty, but may be filled up with any kind of ore or veinstone.[1]

[1] For further information on this subject consult *Ore Deposits*, by J. A. Phillips (Macmillan and Co.); *A Text-book of Ore and Stone Mining*, by C. Le Neve Foster (Charles Griffin and Co.); *Ore Deposits of the United States*, by J. F. Kemp (New York Scientific Publishing Co.); *The Iron-ores of Great Britain and Ireland*, by J. D. Kendall (Crosby, Lockwood, and Son). A valuable paper on the "Genesis of Ore Deposits," by Professor Pošepný, will be found in the *Transactions of the American Institute of Mining Engineers*, vol. xxiii. (1893).

CHAPTER XIV

SURFACE GEOLOGY

In the foregoing pages we have been dealing almost entirely with the solid rocks, their structure and behaviour as constituent portions of the earth's crust. Allusions have been made to their superficial aspects and to the loose accumulations of various kinds by which they are so often concealed. In this chapter let us look cursorily at a few of the aspects of what is sometimes called "surface geology."

And first, of the influence of the solid rocks upon the surface. The distinctive characters imparted by some rocks to scenery have already been referred to.[1] Sometimes it is a question of relative durability. The Chalk escarpment in the south of England, for example, stands out so prominently because it is underlain by more easily degraded sands. Certain portions of a rock may rise high above the rest because of some particular power of resistance they may happen to possess. But one leading influence in the gradual degradation of all rocks is supplied by their *joints*. Every one who has looked into a quarry or railway cutting, or has seen a coast-cliff or a

[1] See *ante*, p. 73.

river-ravine, has had many a joint under his eyes. They are familiar to the quarryman and miner, by whom their directions are always well known, seeing that they determine the course along which quarrying and many mining operations proceed. When the geologist is engaged in hilly or mountainous ground, among crags and rock-pinnacles, or on exposed coast-cliffs, he should

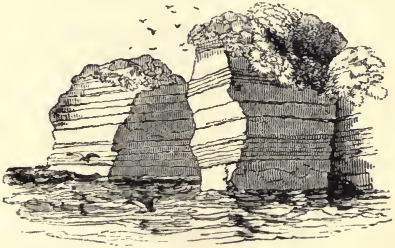


FIG. 78.—Cliff cut into buttresses and recesses by means of the vertical joints of the rocks.

not fail to note with some care the trend of the different joints. He will soon find that they are apt to run in two main directions. And a little further examination will usually enable him to connect the forms of the cliffs with the lines of joint. He will observe how one set of joints runs parallel with the face of a cliff, and is cut across by another series, and how the quadrangular buttresses of rock, which may shoot up perhaps into spiry pinnacles at the top, have their shape first given to them by the intersecting lines of joint (Fig. 78, and also Figs. 12 and 13).

With regard to the superficial deposits of a district, the first aim of the geologist is to gather all available facts, not only from the sections exposed in natural openings, as well as in quarries and other artificial exposures, but, where needful, from the records of well-sinkings, borings, foundation-diggings, and other kinds of excavation. The naming of the deposits,

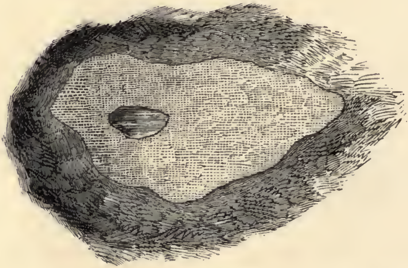


FIG. 79.—Plan of a peat-moss which has filled up a former shallow lake, except one small patch of water.

so far as their lithological characters go, will usually be an easy task; but it may be more difficult to determine their relative order of appearance and the circumstances under which each was formed. A few examples of the kind of examination which may be made will here suffice.

Peat-mosses.—These accumulations of marshy vegetation play an important part in the surface geology of many tracts of Western Europe. In endeavouring to ascertain the history of a peat-moss we have first to consider the form of the surrounding ground, and to judge whether any lake could have probably existed on its site. In some cases, indeed, we may still detect a portion of the original lake, surrounded and continually lessened by the advancing peat (Fig. 79). It is easy to see that at a

FIG. 80.—Section of a peat-moss made in the excavation of peat for fuel.

comparatively recent period the aspect of these tracts of country must have been very different from what it is to-day. Ireland, for example, must have been an island of shallow lakes instead of peat-bogs. Underneath the peat a layer of fresh-water marl may frequently be found full of such typically lacustrine shells as *Lymnea*, *Paludina*, *Planorbis*, and *Cyclas*. These underlying layers should always be diligently searched for bones of mammalia. The wild oxen and deer of the time of the lakes and early morasses have often left their remains at the bottom of the mosses. Human relics ought also to be looked for. Canoes and stone implements are often taken out of peat deposits. Stockaded islets or crannoges may likewise now and then be found. It is always desirable to enlist the co-operation of the workpeople at such places, as they are far more likely than an occasional visitor to come upon objects of interest.

Brick-earth.—Where a thick deposit of loam or earth covers the surface, especially on the slopes of broad river-valleys, attention should be directed to its composition and contents. If it contains occasional land-shells, is not very well stratified, shows no lines of gravel, nor any water-worn stones, and has never yielded either a lacustrine, fluviatile, or marine shell, it may be presumed to be a subærial formation due to the long-continued action of rain or wind, gently moving the soil down to the lower grounds. In the lower parts of the valley of the river Thames thick accumulations of this kind occur, and their antiquity is indicated by the peculiar assemblage of extinct mammalia, including forms of elephant, rhinoceros, and hippopotamus, which they contain.

River Terraces.—These conspicuous features of most river valleys can be easily traced along either side. The observer ascertains the number of terraces (in the valleys of British rivers there are commonly three), also their general average height above each other and above the present mean level of the river. He compares the character of their deposits, and seeks for any information thence obtainable as to variation in the conditions of the river. He keeps his eye constantly open to the possible discovery of organic remains in the terraces, more especially in those of greater altitude, which being the oldest ought to contain the earliest forms of life. Rudely-chipped flint-instruments, or more deftly-fashioned celts occurring

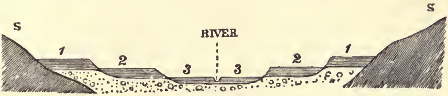


FIG. 81.—River terraces.

in the undisturbed strata of a terrace, prove that man inhabited the district when the river flowed over these strata.

Ancient Beach-lines.—Reference has already been made to the manner in which former levels of the land are marked by terraces containing marine organisms (p. 87). It is obvious that if the land stood long enough at a particular level, the action of the waves might in some places cut a notch along the coast-line as well as spread out a terrace of sand and gravel below high-water mark. The observer may detect many such beach-lines along the coast of Scotland, and the fiords of Norway. He will mark whether they consist of a platform (Norwegian, *Seter*) levelled out of the rock, with a cliff (sometimes perforated with caves) behind it, or whether, the conditions for accumulation of sediment having been favourable, they present a level or gently-sloping terrace of sand and gravel (raised beach). Along the west coast of Scotland these various lines of former sea-margin, sometimes in raised beaches, sometimes in sharply-cut rock platforms, are strikingly conspicuous, those at 50 feet and 100 feet being specially well marked (Fig. 82).

Surface Mounds.—In many districts the field-geologist meets with mounds, as to the origin of which he at first may be puzzled, if indeed he ever comes to any satisfactory conclusion regarding them. The first question

FIG. 82.—Rock terraces (*Seter*) marking ancient shore lines on the south coast of the Island of Mull.

he will ask is, Are they of human construction? Having satisfied himself that they are not, he may try to find some other origin for them by examining their composition, where any available section of them can be found, and the nature of the surrounding ground. Mounds close to the level of a river must always be regarded with a preliminary suspicion of being relics of a formation elsewhere removed by the erosive action of the stream. Mounds of sand and gravel scattered across a district may be due either to the irregular denudation of a once continuous, though perhaps unequal, covering of these loose materials, or to shapes assumed at the time of deposition. In the former case, we should expect to find that sections of the mounds would show the present slopes to have been cut across the bedding of any component strata. In the latter case, we should probably meet with instances of a conformity between the external slopes of the mounds and the inclination of the layers of sand or gravel inside; and this conclusion as to the mounds retaining the original shape assumed by the loose materials at the time of their deposit would be amply confirmed if we saw little basins filled with water or with peat, lying between the mounds, for it is evident that had the slopes been due to atmospheric denudation these hollows must necessarily have been filled up, or rather could not have been formed. Mounds of this kind, deriving their peculiar forms from the circumstances of their formation, are abundant in the north of Britain and in Scandinavia. Some of them lie on open moors or hill-sides, and on watersheds. These are known as *eskers*, *kames*, or *ösar*. A second kind occurs in valleys among the hills, with the forms of rude crescent-shaped ridges curving from side to side of their valleys, sometimes inclosing small lakes: these are unmistakably the moraine-heaps of local glaciers. A third kind consists of a stiff, stony boulder-clay or earth. The mounds of this type are arranged in one general direction across wide tracts of low ground in Ireland and Scotland, where they are known as *drums* or *drumlins*. They belong to the older glacial formations of the country.

Boulders and Travelled Stones.—In most countries where hard rocks of any kind protrude above the soil, scattered blocks of stone may be observed. When these are of large size, and have no visible rock near them, they are commonly assumed to be erratic masses which have been carried by ice to their present positions. Before accepting this interpretation, however, the observer should endeavour to ascertain whether they are really of a material foreign to the district. In many cases, he will find that they are not; that on the contrary, their parent rocks, or at least rocks having precisely the same lithological characters, lie near at hand. Thus, the well-known Druid or Sarsen stones, so abundantly strewn over the plains of Wiltshire, were formerly supposed to have been carried from some extraneous source, but they are now recognised as fragments from a sandy stratum which once covered that part of the country. It is surprising over what a slight inclination large blocks may slowly move in the course of years, as the soil underneath is mixed by worms and roots, and gradually shifted towards lower levels. Sometimes escarpments which once supplied a crop of blocks to the slopes below, get gradually buried under their own *débris*, and are in the end earthed and grassed over, so that those blocks which may still remain exposed, and have survived the crags that supplied them, might be taken for far-transported erratics. It is essential, therefore, when the observer wishes to determine beyond question whether a particular boulder is due merely to the disintegration of a rock *in situ* or to transport from some distance, first of all to make sure that there is no parent rock in the immediate vicinity to which the rock can possibly be referred, either because its composition is different, or because its position shows that it could not have come by mere ordinary decay and removal. If he can prove that the block is foreign to the district, or that though rocks of the same character occur they could not have supplied the block in question except by the intervention of some unusual agent which moved it into its present position, he will establish that at all events the boulder is a transported one.

What may have been the agent of transport must be decided by the particular evidence in each case. In a river valley, blocks within reach of the present or former currents may have been moved downward by river floods. Waves can throw up blocks of considerable size, and even quarry them out of their solid beds in the parent rock at heights of seventy feet or more above high water. To the freezing of the water of rivers, lakes, or the sea around shore-blocks, and the subsequent breaking up of the ice, the transport of considerable masses of rock along shore has been due. Icebergs have been observed at sea with blocks of stone and heaps of rock-rubbish lying upon them. Glaciers transport enormous quantities of loose blocks of rock and earth from the upper valleys. Undoubtedly ice has been the great agent in the distribution of erratic blocks; but whether in the form of floating ice, of glaciers, or of a great general sheet of land-ice, must be decided in each district, not only from the evidence of the blocks themselves, but from the other data obtainable as to the glaciation of the country.

Glaciation.—Only a very few words are possible here on this wide and fascinating subject, regarding which of course the reader has ample means of information from the voluminous literature already devoted to it. Certainly among the many superficial characters of interest found in the northern parts of the northern hemisphere, as well as in mountain-tracts in other regions of the globe, few offer such temptations to their study as the smoothed and striated surfaces left upon rocks by the passage of sheets of ice across them. They occur in such unlooked-for places, and among surroundings now suggestive of almost any other physical condition than that of an Arctic ice-sheet. When the field geologist has once seen this kind of surface, he is not likely to confound it with any other. The only one for which it sometimes might be mistaken is that termed *slickensides*, where the two walls or faces of

FIG. 83.—Ice-worn hummocks of rock, the arrow pointing in the direction of the ice-movement.

a joint or fault have slid upon one another so that each side is rubbed smooth, polished, and grooved. But a little practice and the study of good examples will give the observer such confidence in discriminating between them as he cannot acquire in any other way. The glacial striation is a merely superficial marking. The ruts are often paler than the rest of the rock, as scratches on a fresh rock-surface are, and though marked in each case by one prevalent direction, are found often to cross each other obliquely. There is generally great variety in the size and depth of the striæ; some being such fine lines as might have been graven by the point of a quartz-crystal, others closely adjacent being blunt and coarse, as if produced by the edge of an angular block of stone. Moreover, the striated surfaces are undulating and dimpled, the striæ descending into and rising out of these inequalities. Here and there, the groovings may be seen mounting up a sloping boss of rock, but if the inclination of the rock becomes steep, the markings diverge on either side of it. On a vertical crag, they may be found running horizontally along its face. Now a slickensided surface presents, in many respects, a contrast to these features. It is almost always coated with some mineral glaze or incrustation, such as hæmatite, calcite, chlorite, or quartz, which may have taken a cast of the striæ on the rock, or may subsequently have been itself striated. In innumerable instances, the slickenside is not confined to one surface, but may be detected in successive planes inside the rock, showing it to be an internal condition of the mass due to the shifting and grinding together of its parts, and not to a mere superficial agent like moving ice. The striæ of slickensides are close set, parallel, and tolerably equal in breadth and depth, and they lie on flat surfaces which do not undulate in the manner so characteristic of glaciated rocks.

It is important to take with the compass the direction of the glacial groovings and striæ on rocks. If possible the observer should at the same time determine from which quarter the ice has moved. This may often be done by noting in what direction little prominences and the edges of angular projections are rounded off, and to which side the still rough and unstriated portions look.

The ice must evidently have moved from the quarter to which the smoothed faces are presented, and towards the quarter to which the rough parts are turned. This is shown in Fig. 83, where the arrow indicates the trend of the ice movement. The way in which an observation of this kind may be indicated on the map is shown in the index of signs in Fig. 4. By a sufficient number of such observations in a district, the path of the ice across it may be clearly expressed.

Another useful method of supplementing this evidence from rock-striations as to movements of the

FIG. 84.—Striated stone from the boulder-clay.

ice cannot usually be put into practice until after the observer has made some considerable acquaintance with the geology of a wide region. In countries which have been under ice, and where the rocks retain the characteristic ice-markings, the surface commonly presents abundant accumulations of boulder-clay, gravel, and other deposits belonging to different conditions of the long Glacial Period. A search through the stones and boulders of these deposits will in most cases disclose the fact that the fragmentary materials have been moved a greater or less distance from their parent rocks. In the clays, the stones (Fig. 84) are often as well striated as the solid rock below. Let us pick out at random two or three hundred stones from any section of boulder-clay or moraine-stuff, and note down the proportions in which each variety of rock occurs among them. We shall find perhaps that 50 or 60 per cent may have been derived from rocks in the immediate vicinity, that 20 or 30 per cent have perhaps come a good many miles, while the

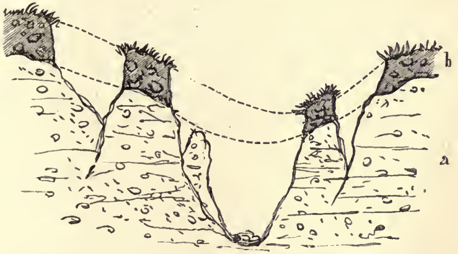


FIG. 85.—Section of a stream-course in the Old Red Sandstone, Fochabers; (*a*) conglomerate; (*b*) glacial drift.

remainder (usually small in size) may possibly be traced to some of the most distant rocks in the drainage-basin of the region. We learn from such an analysis the general direction of the ice-stream and see that it agrees with the evidence furnished by the striæ on the rocks.

Ancient valleys buried under Drift.—Among the interests of field-geology none appeal more forcibly to the imagination than those which belong to the traces of a vanished land-surface, side by side with the land-surface of the present day. Reference has been made

(p. 119) to the extraordinary group of primeval mountains now in course of exposure by denudation in the north-west of Scotland. The observer may often encounter on a more modest scale traces of old valleys, which have been buried under the glacial drift, and have been brought to light in recent times by the wearing down of the overlying deposit. Fig. 85 represents a section cut by a small stream in the Old Red Conglomerate near Fochabers, in the north of Scotland. It will be seen at once that the hollow existed before the boulder-clay was laid down in it. But rain and runnels have already cut through the drift which is now reduced to fragments, capping the columns into which, by the same agents, the conglomerate has been carved.

PART II

INDOOR-WORK

CHAPTER XV

NATURE OF INDOOR-WORK. GEOLOGICAL SECTIONS

WHEN a geologist returns to his quarters after a long day in the field, if he means to make further use of the information which he has collected in the course of his walk, he ought on no account to allow himself, no matter how seductive may be the attractions of his comfortable quarters, to dismiss from his mind the labours of the day until he has looked over his notes, and filled in, while still fresh in his memory, all details which he did not find time to jot down on the ground. This task sometimes demands not a little self-denial on the part of one who feels that he has worked well and earned his *siesta* with a pleasant book or the latest newspaper. But it must be done, and done then. Put off till next evening, the duty is more irksome, and the details are already beginning to be elbowed out of memory by the host of new ones which have in the interval been observed.

It is particularly useful to enter in the note-book sections of the ground just examined, giving what may be at the time the observer's interpretation of the structure of the rocks. Even though these are thrown aside in the end, or superseded by others based on wider experience, they serve their purpose by fixing in the mind what has been seen, and directing attention to the points on which the evidence is defective. A good working hypothesis, so useful in all kinds of scientific work, when employed as a help and not as a master, is specially serviceable in field-geology. One such hypothesis after another may have to be abandoned, but each performs its work in leading the observer nearer to the true solution of his problem. And it is as embodying his working hypothesis of the day that these rough tentative sections in the note-book, made while all the first impressions are still fresh and clear, derive their chief value.

If the geologist is gifted with any power of sketching he will take care that his pencil drawings or outlines—all perhaps that his time and work will allow in the field—are secured before getting rubbed, as they are sure to do if carried without precaution in his everyday note-book. They may be fixed in the ordinary way with weak gum-water, isinglass, white of egg, or skimmed milk. But I have found it preferable to wash them with sepia, indian-ink, Payne's grey, or some other medium. The pencil-lines are thus fixed, while at the same time, with two or three tints of colour, the sky and relative tones or values of the landscape may be given. If water-colour can be rapidly used in the field this is still better; but in my own experience the temptation to make a sketch instead of a geological diagram is so great that the amount of field-work suffers diminution. Hence I would advise that the field-work be done first, and that the observer, having thus been over the ground and chosen his points of view, should return with his sketch-book and colour-box, and use them with no inward consciousness that he ought to be up and wielding his hammer. An occasional thoroughly wet day, when work out of doors is impossible, affords an excellent opportunity for fixing the drawings, determining rocks, drawing sections, writing up notes, and indeed for all other kinds of indoor employment.

In a former chapter I spoke of certain portions of his labours which the field-geologist could only accomplish within doors. I propose now to describe three kinds of indoor-work. (1) Section-drawing; (2) chemical and mechanical testing of rocks; and (3) the examination of rocks with the microscope.

SECTION-DRAWING

The construction of geological sections is placed here among the indoor employments of the field-geologist, although if they are to be as full and perfect as possible, their outlines must be traced on the ground. A section on a true scale, vertical and horizontal, may be prepared by measurement on the ground in the ordinary way with chain and theodolite. But this is an operation of ordinary land-surveying which need not be described here. Or if the country has been accurately contoured, as in the Ordnance Survey maps, a section may be drawn by using the contour-lines.

The more clearly a geological map represents the structure of a country, the less need is there for any additional explanation, so that a perfect map, large in scale and detailed in execution, should be nearly independent of sections or other assistance, except for data, which cannot be expressed upon a map. But such a map can comparatively seldom be made, and clearly constructed sections always save much time and labour, as they enable the structure of a region to be seen and comprehended almost at a glance. We must usually be content with a map on a small scale, an imperfect topography, and other defects, which compel us to supplement the map with lines of section, so drawn as to convey to the eyes of others exactly what we have ourselves seen, or believe, to be the geological structure of the district or country in question.

A section may either be horizontal or vertical, that is, it may show what would be seen if a deep trench could be cut across hill and valley, so as to expose the relations of the rocks to each other, or it may exhibit the arrangement and thicknesses of the rocks as they would appear if we could pile them up into a tall column one above another in their proper order of succession. On a small scale, Figs. 33 and 64 may be taken as examples of vertical sections. This kind of section is chiefly of use in detailed work, as, for instance, among coal-fields, where the various strata of one pit or part of a district are to be compared with those of another, or in localities like the coast-sections of the Tertiary rocks of the Isle of Wight, where every stratum is exposed to view. Evidently a section of this kind requires good exposures of rock and careful measurement.

The horizontal section, on the other hand, must often be constructed where exposures of rock are few, where minute measurements are impossible, and where the highest skill of the field-geologist is taxed to unravel the meaning of the facts he notes upon the surface, and to show their bearing upon the relations of the rocks below ground. The first point I would remark in the drawing of horizontal sections is, that if not at the beginning, at least in some part of his experience, he will find the great advantages of plotting them on a true scale, that is, with the height and length on the same scale, and thus training his eye to the true proportions of the different parts of the topography. Of course this is often impossible, for the ground may be low, and to show its true form in a section might require an extravagant and unnecessary length of paper. Still the geologist who would preserve, as he should, the relations between the external form of the ground and the structure of the rocks below it, will always endeavour to exaggerate the height of his sections as little as possible. I believe that nothing has tended so much to perpetuate erroneous notions regarding the physiography of the land as such distorted sections, sometimes almost grotesque in their exaggeration of natural forms.

As an example of the disregard which some able observers have had for truth of outline in their sections, there are inserted on the following page two sections of the same hill. On one of these (A), an eminent mineralogist, seems to have been content to represent in a kind of diagrammatic way the order of the formations, heedless of the utterly unnatural shape of his hill. The other section (B) shows the true outline of the ground, on the scale of six inches to a mile, vertical and horizontal, with the relative position of the rocks correctly inserted.

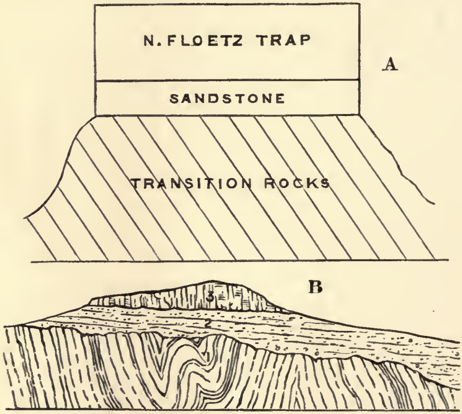


FIG. 86.—Illustrations of geological section drawing.

A further and familiar illustration of the effects of this neglect of the true proportions of the ground is offered to us by the case of the "London Basin." I presume most readers, when they meet with that phrase, think of a deep bowl-shaped hollow filled with clay and surrounded by a rim of chalk hills, and they probably recall one of the sections in popular manuals and text-books by which this impression was originally given to them. If, however, we construct a section across the London basin on a true scale, or examine that which has been constructed and published by the Geological Survey on the scale of six inches to a mile, we learn that so flat is the basin, so small the thickness of clay (500 feet) in proportion to the breadth of country over which it is spread (24 miles), that we need to look with some little care to be assured that there is really any basin at all.

The next point to be attended to in the construction of a horizontal section is the choice of the line of ground across which it is to be drawn. It may be designed either to show the general structure of the country or the arrangement of the rocks in some particular part of it. In any case, while taking it over those portions of the ground where the structure is best seen, we should always bear in mind that it must pass as nearly as possible at a right angle to the strike of inclined strata. Obviously, a section coincident with the strike would make highly-inclined beds look horizontal.

When the time arrives for a section to be drawn, the first thing is to insert the outline of the ground. The actually observed geological data, such as dips, faults, and other facts, are then placed upon that outline. If necessary, search is made on either side of the line of section for additional materials to fill in the blanks in the section. The lines found at the surface are then prolonged downward, and the section is filled in. To make these stages more clearly understood, let us suppose that we are required to draw a section on a true scale (say of six inches to a mile) across a piece of ground. We fix on some datum-line, the sea level, for instance, on which to erect our verticals for the heights. Having obtained the correct measurements of the surface from our own levellings, or those of other surveyors (in Britain the contoured maps of the Ordnance Survey are invaluable for this purpose) we proceed to mark off from

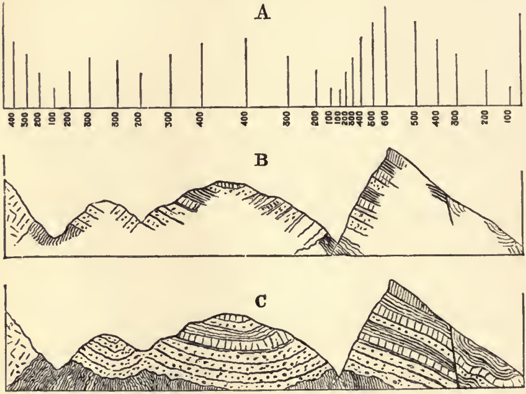


FIG. 87.—Stages in the construction of a geological section.

our datum-line a series of points, the height of each of which is known. How this is done is shown in Fig. 87, A. A line is then drawn, connecting all the points together, which gives, it will be observed, the general contour of the ground. To ensure greater fidelity of detail it may be well to walk again over the ground with the plotted section in hand, so as to be able to fill in any little inequalities of surface, and at the same time to look once more for evidence as to the nature and structure of the rocks below. The drawing in Fig. 87 B, may be taken to represent the outline as so modified by a visit to the ground. On this same drawing all the geological data are inserted which are supposed to be actually seen, either on the line traversed by the section or in the immediate vicinity of it. But a more extended examination of the district would no doubt supply many data not obtainable on the precise course of section, and permit the lines to be prolonged downward, and the whole section to be filled in somewhat in the manner shown in C. The section in Fig. 28 shows the structure of the country represented in the map, and illustrates the application of many of the terms which I have made use of in these pages.

CHAPTER XVI

MECHANICAL AND CHEMICAL TESTS IN THE IDENTIFICATION OF MINERALS AND ROCKS

It often happens, especially in the early years of his experience, that the geologist meets with rocks which none of the tests available in the field enable him satisfactorily to recognise. In such cases, as already remarked, he detaches one or more fresh chips of each puzzling variety, and carries them home for determination by more precise processes. He may, in the first place, apply some simple physical and chemical tests. Detailed chemical analysis cannot of course be attempted in the ordinary conditions of field-work, but much may be learnt by a few easily performed experiments.

1. *Testing for Hardness.*—Reference has already been made (p. 67) to the relative hardness of rocks as a means of discriminating different kinds. This test is of most value in the study of minerals; but is not without practical value in the field, as well as indoors, in the investigation of rocks. The scale of hardness adopted for minerals and applicable also to rocks is as follows :—

1. Talc.	6. Orthoclase.
2. Rock-salt.	7. Quartz.
3. Calcite.	8. Topaz.
4. Fluor-spar.	9. Corundum (Emery).
5. Apatite.	10. Diamond.

A rock which can be easily scratched with the finger-nail, like many chloritic-schists, may be said to have one degree of hardness, or H 1; rocks possessing the hardness of rock-salt (2) can be less readily scratched with the finger-nail. The pocket-knife easily marks a limestone or crystal of calcite (3), which, on the other hand, resists the finger-nail; a little more pressure is required to mark a crystal of fluor-spar (4), and still more one of apatite (5). Rocks possessing the sixth degree of hardness can be scratched with the knife with difficulty, while when they present greater hardness than about $6\frac{1}{2}$ degrees they resist the knife and even turn its edge, or take a streak of steel. Hence as rocks of this resisting power are almost always siliceous, the application of the knife furnishes a convenient means of discriminating them.

Obviously in trying the hardness of rocks we must see that we are in possession of fresh undecomposed surfaces. The effect of weathering is generally to loosen the texture of a rock, and make it yield more readily to abrasion, and as the influence of this superficial decomposition may extend for several feet or many yards into a rock, it is not always practicable to obtain a specimen sufficiently fresh to admit of the application of this test. It must be remembered that the hardness of a rock, even when quite fresh, may appear less than from the nature of its component minerals we might expect it to be. The pressure of the knife bruises and cuts through the edges of crystalline grains which lie close together, when a good deal more force will be required to scratch the cleavage face of one of these grains. The test of relative hardness serves usefully to distinguish various compact rocks from each other, when there is no obvious internal difference by which the eye could discriminate between them. Some pale dull felsites resemble certain limestones and dolomites, but their much greater hardness in a fresh state serves at once to mark them. Again, some exceedingly compact dark volcanic rocks, such as basalts and aphanites, might at first be mistaken for clay-band ironstones or black limestones or mudstones, but they will easily be distinguished by their superior hardness and weight.

2. *Specific Gravity.*—Determinations of the specific gravity of rocks may be usefully made when the geologist has brought home some rock-specimens about the composition of which he may be in doubt. By this means, for instance, he can readily separate his limestones which have a specific gravity of about 2.72 from his dolomites which are heavier (2.85). In like manner, he can discriminate acid from basic igneous rocks, and may form a shrewd guess as to what special rock-species his specimens should be assigned. The most convenient instrument for determining the specific gravity of rocks in the progress of field-work is undoubtedly Walker's balance,[1] which consists of a small steel-yard divided into inches and tenths. The specimen to be determined is hung by

[1] This useful and portable instrument is made by G. Lowdon, Reform Street, Dundee, and can be obtained through any instrument-maker.

a thread from the longer part of the bar in such a position as to counterbalance the weight on the shorter part. The reading gives the weight of the specimen in air. The specimen, still hanging from the bar, is then immersed in a tumbler of distilled water at a temperature of 60° Fahr. and moved along until it again counterbalances the weight. This new reading gives the weight of the specimen in water. The specific gravity is obtained by dividing the weight in air by the loss of weight in water.

In connection with the determination of specific gravity, reference may be made here to a convenient method of making use of the relative weights of minerals as a means of readily separating them when they are constituents of rocks. It is often desirable to isolate the various minerals in a crystalline rock, not only for chemical analysis but for examination with the microscope. For this purpose, liquids of high specific gravity are used, in which some of the minerals will float, while others sink. By varying the density of the solution, the various ingredients of a rock, when they are of different specific gravities, may be obtained separately. The rock to be examined is crushed in a metal mortar, care being taken to prevent any of the steel of the mortar from being removed. The liquids in most general use are Sonstadt's solution of potassium-mercuric iodide, with a maximum density of 3.196, and "Klein's Solution" of cadmium-borotungstate, which has a density of 3.28, and is more serviceable than Sonstadt's. Both these solutions can readily be diluted with water. Methylene iodide is also available with a density of 3.33, which can be increased to 3.65.

3. *Treatment with Acid.*—In the list of a field-

geologist's accoutrements an acid-bottle, or some powdered citric acid to be used with a drop of water, was included (*ante*, p. 30). A little acid will at once tell by a brisk effervescence if a rock is a limestone or is markedly calcareous. By the same means we may often trace the decomposition of such rocks as dolerite to a considerable distance inward from the surface; the original lime-bearing silicate of the rock having been decomposed by infiltrating rain-water, and partially converted into carbonate of lime. This carbonate is far more sensitive to the acid-test than the other carbonates usually to be met with among rocks. A drop of weak cold acid suffices to produce abundant effervescence even from a crystalline face. But the effervescence becomes more marked if we apply the acid to the powder of the stone. For this purpose a scratch may be made and then touched with acid. By this means a copious discharge of carbonic acid may be obtained from some rocks where otherwise it might appear so feebly as perhaps even to escape observation. Some carbonates, dolomite for example, are hardly affected by acid until heated. In other cases, the acid requires to be used very strong, as with siderite.

It is a convenient method of roughly estimating the purity of a limestone to place a fragment of the rock in weak hydrochloric acid. If there is much impurity (clay, sand, oxide of iron, etc.), this will remain behind as an insoluble residue, and may then be further tested chemically or examined with the microscope. Of course the acid may attack some of the impurities, so that it cannot be concluded that the residue absolutely represents everything present in the rock except the carbonate of lime, but the proportion of non-calcareous matter so dissolved by the acid will usually be extremely small.

If the student possesses chemical knowledge, he may proceed to test the acid solution he obtains from a pulverised rock and may detect the bases; but as a rule detailed analysis can hardly be undertaken by the geologist in the field.

Some acquaintance with chemical reactions, indeed, will be found of great service in the identification of rocks and of their constituent minerals. It is commonly the case that minerals about which the observer may be doubtful are precisely those which, from their small size, are most difficult of separation from the rest of the rock preparatory to analytical processes. The mineral apatite, for example, occurs in minute hexagonal prisms which on cross-fracture might be mistaken for nepheline, or even sometimes for quartz. If, however, a drop of solution of molybdate of ammonia be placed upon the crystal, a yellow precipitate will appear if it be apatite. Nepheline, which is another hexagonal mineral likewise abundant in some rocks, gives no yellow precipitate with the ammonia solution, while if a drop of hydrochloric acid be put over it, crystals of chloride of sodium or common salt will be obtained. These reactions can be observed even with minute crystals, by placing them under the microscope and using an exceedingly attenuated pipette for dropping the liquid on the rock.

4. *Blow-pipe Tests.*—The chief chemical tests available for the field-geologist are those which he can perform with the blow-pipe. These he will find to be simple,

easily applied, and requiring only patience and practice to give him great assistance in his determination of minerals. If unacquainted with blow-pipe analysis he must refer to one or other of the numerous text-books on the subject, some of which are mentioned below.[1]

The apparatus required for ordinary blow-pipe work is exceedingly simple. For his early practice the student will find the following sufficient:—

1. Blow-pipe.
2. Thick-wicked candle, or a tin box filled with the material of Child's night-lights, and furnished with a piece of Freyberg wick in a metallic support.
3. Platinum-tipped forceps.
4. A few pieces of platinum wire in lengths of three or four inches.
5. A few pieces of platinum foil.
6. Some pieces of charcoal.
7. A number of closed and open tubes of hard glass.
8. Three small stoppered bottles containing carbonate of soda, borax, and microcosmic salt.
9. Magnet.

To this list he will afterwards add as he gains knowledge and confidence. The whole of the absolutely necessary apparatus for preliminary, and even for general

[1] The great work on the blow-pipe is Plattner's, of which an English translation has been published. Elderhorst's *Manual of Qualitative Blow-pipe Analysis and Determinative Mineralogy*, by H. B. Nason and C. F. Chandler (Philadelphia: N. S. Porter and Coates), is a smaller but useful volume; while still less pretending is Scheerer's *Introduction to the Use of the Mouth Blow-pipe*, of which a third edition by H. F. Blanford was published in 1875 by F. Norgate. An admirable work of reference will be found in Professor Brush's *Manual of Determinative Mineralogy* (New York: J. Wiley and Son). See also Professor G. A. J. Cole's *Aids in Practical Geology*, third edition, 1898, pp. 37-78.

Locality, etc., of specimen.	I. Behaviour in closed tube.	II. In open tube.	III. On charcoal.		IV. On platinum forceps or wire (or on foil with soda).			Other reactions. Remarks.
			Alone (*a*).	(*b*) With soda.	(*a*) Alone.	(*b*) With borax.	(*c*) With microcosmic salt.	

use, may be packed into a box which will go into the corner of a portmanteau.

The annexed Scheme shows the method of procedure which the observer may follow in the blow-pipe determination of a mineral, extending it to further reactions if necessary. He will find it advantageous to write down, under each head, the behaviour of the substance, before he proceeds to the next operation.

5. *Magnetic Analysis.*—Many dark crystalline rocks contain much magnetite or other magnetic mixtures of iron oxides. Some idea of the relative proportions of these ingredients may be formed by reducing a specimen of the rock to the finest powder in an agate mortar, and then weighing out so many grains of the powder. If a hammer has been used in collecting the specimen, the latter should be carefully washed and rubbed with a brush before being reduced to powder. The magnet, protected by fine tissue-paper, may then be inserted into the powder, and the magnetic particles which adhere to it should be dropped into a separate dish, which is easily done by pulling the magnet slightly away from the paper, when the iron particles at once fall off. The process should be repeated until no more magnetic grains adhere to the magnet. An additional proportion of iron grains may, however, be obtained by grinding the powder in the mortar with water, allowing it thereafter to dry thoroughly, and then when it has once more been bruised in the mortar, placing the paper-protected magnet upon it. Minute black specks will be observed adhering to the paper. The magnetic grains in the separate dish should be examined with a lens to see that no considerable

quantity of the other minerals of the rock may be adherent to them, in which case they may be gently pounded with water in the mortar, dried, and picked out afresh with the magnet. The magnetic residue obtained represents nearly the proportion of magnetic iron in the rock; but is almost always under the truth, because some of the magnetic iron is in microscopic particles, inclosed within other constituents of the rock. This rough method of analysis may be applied to basalt, dolerite, and similar rocks. By means of an electro-magnet the minerals which contain iron, but are not in the ordinary sense magnetic, may be extracted.

Important Minerals in Rocks.—To assist the learner in his field-work the following list is given. It contains the more important minerals which occur as essential or accidental constituents of rock, and indicates briefly the conditions under which each may be expected to be found. But for the chemical and microscopic characters of these minerals, he must refer to a text-book of mineralogy, or to one of the works referred to in the footnote on p. 250.

List of the more Important Minerals which enter into the Composition of Rock-masses.

		I. Essential Constituent. II. Accessory Ingredient.
NATIVE ELEMENTS.	Graphite . . .	II. Scales and layers in gneiss, schists, slates; also as a result of the alteration of coal by intrusive igneous rocks.
	Sulphur	II. Chiefly at volcanic orifices and as a product of decomposition among Tertiary strata.
	Copper	II. Not infrequent in thin veins and plates among some of the Palæozoic volcanic rocks.
SULPHIDES.	Pyrite	II. Abundantly diffused in rocks of all ages in detached crystals and in veins.
	Marcasite . . .	II. Especially among sedimentary rocks, often taking the place of organic remains: very liable to decomposition.
	Chalcopyrite . .	II. Veins chiefly.
	Galena	II. Scattered grains, but chiefly in veins.
	Blende	II. Usually with galena in veins.
FLUORIDE.	Fluor spar . . .	II. Veinstone in stratified and unstratified rocks: occasionally in cavities of crystalline rocks.
CHLORIDE.	Rock-salt . . .	I. In beds especially associated with red strata: sometimes II. as scattered cubes in red sandstones, clays, and other strata, but then generally replaced by clay, etc.
OXIDES. Anhydrous.	Quartz and its varieties	I. Abundant in many crystalline rocks, *e.g.* granite, quartz-porphyry, liparite; and in fragmental rocks, as sandstone, greywacke, etc.
		II. Frequent in veins and cavities of rocks of all ages as an infiltration product.
	,, Chalcedony and varieties	II. Filling or lining cavities especially of old volcanic rocks; introduced by infiltration.

			I. Essential Constituent. II. Accessory Ingredient.
Oxides.	Anhydrous.	Hæmatite	I. In some crystalline rocks: in beds among foliated rocks and as a colouring-matter in fragmental rocks. II. Abundant in veins and cavities of rocks as an infiltration product.
Oxides.	Anhydrous.	Magnetite	I. In many foliated rocks, *e.g.* chlorite slate; abundantly in minute crystals in many igneous rocks, as dolerite, basalt, gabbro, etc.
Oxides.	Anhydrous.	Ilmenite	I. In many foliated rocks; also abundant in some volcanic rocks, as dolerite, gabbro, etc.
Oxides.	Hydrous.	Limonite	II. Common as an alteration-product of previously-formed hæmatite in veins and cavities of rocks.
Oxides.	Hydrous.	Wad, Psilomelane	II. As a dark earthy substance in cavities and veins of rocks, and as dendritic markings in the minute fissures of such close-grained rocks as felsite-porphyry and lithographic limestone.
Aluminous Silicates. Anhydrous.	Orthoclase or Monoclinic Felspar.	Orthoclase and Varieties.	I. Abundant among both ancient and modern crystalline rocks, as granite, gneiss, quartz-porphyry, liparite, trachyte, obsidian, etc.
Aluminous Silicates. Anhydrous.	Plagioclase, or Triclinic Felspars.	Oligoclase, Albite	I. Abundant as the triclinic felspars of older crystalline rocks, as in granite, syenite, etc.
Aluminous Silicates. Anhydrous.	Plagioclase, or Triclinic Felspars.	Anorthite, Labradorite	I. Abundant, more especially among volcanic rocks of all ages from palæozoic up to recent; found also among ancient foliated rocks, as the gneiss of Labrador and in some granites.
Aluminous Silicates. Anhydrous.		Leucite	I. An essentially volcanic mineral, only found in lavas and tuffs of later geological periods.

		I. Essential Constituent. II. Accessory Ingredient.
ALUMINOUS SILICATES. Anhydrous.	Nepheline	I. In some volcanic rocks in minute prisms; also massive in metamorphic rocks.
	Hauÿne	I. Only found in post-tertiary lavas.
	Nosean	I. Like Hauÿne, a volcanic mineral of late geological date, said to occur in almost all phonolites.
	Muscovite (Potash-mica) and varieties	I. Abundant in old crystalline rocks, both massive and foliated—granite, gneiss, mica-schist, greisen, etc.; also in sandstones of all ages.
	Biotite (Magnesia-mica) and varieties	I. Abundant in many crystalline rocks. II. As an occasional alteration-product in many hornblendic and augitic rocks, and in sedimentary rocks in the aureole of metamorphism round granite.
	Chiastolite	I. Abundantly diffused through some metamorphic slates, hence called chiastolite-slates.
	Kyanite	I. In small granular forms in some crystalline rocks, *e.g.* kyanite-rock; also in beds and veins in gneiss and other schists.
	Tourmaline	I. In some granites, and in the veins associated with and proceeding from these granites.
	Garnet	I. Abundant in many foliated rocks, as in mica-schist and some varieties of gneiss.
	Epidote	I. In some foliated rocks, as gneiss and mica-schist. II. As an alteration-product in many rocks, as in diorite, diabase, altered sandstone, etc.
	Cordierite (Iolite)	I. In geodes and veins among older crystalline rocks, as granite, gneiss, and several schists; one variety, cordierite-gneiss, contains it abundantly.

		I Essential Constituent. II. Accessory Ingredient.
ALUMINOUS SILICATES. Hydrous.	Zeolites	II. This interesting family of minerals is due to the alteration of anhydrous aluminous silicates, chiefly felspars. The several species occur as secondary products in veins and cavities of rocks, especially of such as contain abundant felspar. The amygdaloidal cavities of basalts and other basic volcanic rocks furnish many varieties.
	Ottrelite . . .	I. In some varieties of slate, as that of Ottrez, Luxembourg, whence the name ottrelite slate.
	Kaolin	II. Arising from the decomposition of felspar; apt to occur wherever a felspar-bearing rock, such as granite, is exposed to a moist climate.
MAGNESIAN SILICATES. Anhydrous.	Hornblende . .	I. Abundant as a constituent of many massive crystalline rocks, *e.g.* syenite and diorite; of many foliated rocks, as hornblende-schist, and varieties of gneiss.
	Augite	I. The black variety abundant among volcanic rocks—basalt, diabase, etc.; the paler kinds among granitic and foliated rocks, and not uncommon among crystalline limestones.
	Diallage . . .	I. One of the constituents of gabbro; also found in serpentine and hypersthene rock.
	Enstatite . . .	I. One of the constituents of the rock called Lherzolite; occurs also in some diabases, serpentines, and in meteorites.
	Bronzite . . .	I. In some serpentines and basalts; also in some meteorites.

			I. Essential Constituent. II. Accessory Ingredient.
Magnesian Silicates.	Anhydrous.	Uralite . . .	II. A mineral having the crystalline form of augite but the internal fine fibrous character of hornblende, with sometimes a central core of still unaltered augite. In some old porphyritic rocks —Urals, Norway, Alps, Scotland.
		Smaragdite . .	I. A constituent of the rock called eclogite and some forms of gabbro.
	Hydrous.	Talc	I. Abundant among foliated rocks, some of which (*e.g.* talc-schist) consist largely of it. II. As an alteration-product among crystalline rocks.
		Chlorite . . .	I. Constituting almost the whole of the rock termed chlorite-slate, and found among other foliated and crystalline rocks. II. Frequent as an alteration-product in rocks containing hornblende, augite, olivine, or other anhydrous magnesian silicate.
		Serpentine . .	I. Constitutes entire rock-masses, but these appear in all cases to have been originally anhydrous, often olivine-rocks. II. Frequent as an alteration-product, particularly in rocks containing olivine.
		Delessite . .	II. Alteration-products in crystalline rocks, especially volcanic masses rich in magnesian silicates; occur in kernels filling cavities, as incrustations round nodules, or in irregular veinings and blotches.
		Saponite . .	(shared with Delessite)
		(Celadonite)	(shared with Delessite)
		Glauconite . . (Silicate of Iron and Potash.)	II. Abundantly diffused through some sandstones and limestones; found also as an alteration-product among many old augitic and hornblendic volcanic rocks, lining cavities or running in threads through the altered mass.

			I. Essential Constituent. II. Accessory Ingredient.
Carbonates.		Calcite	I. Common as limestone or the calcareous constituent of stratified rocks. II. Very abundant as an alteration-product, filling cavities or running in veins and threads through rocks.
		Aragonite	II. Under similar circumstances as calcite, but less abundant.
		Dolomite	I. Occurs in beds and layers with limestone, red marl, sandstone, etc. II. In veins and cavities and along the edges of intrusive igneous rocks.
		Siderite	I. In beds and nodules associated with shale, coal, etc. II. Occasionally in veins and cavities of rocks.
Sulphates.	Anhydrous.	Barytes	II. Common as a veinstone; also found in cavities of amygdaloidal rocks.
		Celestine	II. In cavities and veins in limestone, sandstone, and in some old volcanic rocks.
		Anhydrite	I. In beds, associated with limestone, red sandstone, or rock-salt.
	Hydrous.	Gypsum	I. In beds with red strata, rock-salt, etc. II. In veins and strings through different rocks.
		Alums	II. Aluminous rocks, containing iron sulphides, exposed to weathering are apt to decompose, and various alum-salts appear as an efflorescence.

		I. Essential Constituent. II. Accessory Ingredient.
PHOSPHATES.	Apatite	I. Abundant in some metamorphic regions, both in layers and in veins ; an essential constituent of many crystalline rocks, as varieties of granite, diorite, diabase, gabbro, and dolerite. II. Common as a veinstone in some metalliferous districts.
	Vivianite	II. In veins associated with metallic ores ; also as a blue earth in bogs and other places where animal remains have decayed, and as a peach-bloom on some ichthyolites.
TITANATE.	Sphene	I. Abundant in some granites, syenites, gneisses, schists, and metamorphic limestones.
HYDRO-CARBONS.	Asphalt	II. Occasionally disseminated in grains or filling veins and cavities of sandstone or other rocks.
	Naphtha	II. Occasionally in cavities of rocks, or coming to the surface either alone or with spring water.
	Anthracite . . .	I. In beds, like ordinary coal. II. In cavities of rocks, particularly in association with intrusive igneous masses ; also diffused in minute grains, giving a black, coally aspect to some rocks.

CHAPTER XVII

MICROSCOPICAL INVESTIGATION

FREQUENT reference has been made in the foregoing pages to the advantage of studying minerals and rocks under the microscope. By this means we are enabled to trace the minuter structures of the earth's crust, and to follow many of the stages in the formation of its rocks. We can tell which mineral of a rock crystallised first, and indeed can follow the successive phases of crystallisation, in such a way as to explain many otherwise unknown parts of the history of the rocks. Moreover, by this method we can trace the subsequent changes which rocks have suffered in the chemical alteration of their minerals by percolating water, with the resulting secondary products. While a chemical analysis informs us of the ultimate chemical constitution of a rock, a microscopic analysis brings before us its mineralogical composition, showing in what forms the chemical elements have been combined, and how diverse two rocks may be in structure and texture, though in chemical composition nearly alike.

The field-geologist, however, besides these inquiries, often needs some ready means of determining the nature and petrographical grade of rocks which he cannot satisfactorily name by any of the usual methods available to him. By far the most valuable aid in this respect is supplied to him in the examination of powders or of thin slices of rocks with the microscope. He may essay to make his own preparations, though when he can have the slides satisfactorily made for him he may save time for other work, and have the slides better made.

Pulverisation.—Much may be learnt regarding the mineral constituents of rocks by examining their powders. For this purpose a small fresh fragment of the rock to be studied is placed in a steel mortar and reduced to powder, but without any grinding motion that would break down the particles into dust. The powder thus obtained should be sifted on fine muslin. A little of it is then washed in a solution containing two or three drops of strong gum in an ounce of water, to remove the finer dust and leave the clean rock-particles that are to be examined. These particles are then lifted upon a clean glass-slide and carefully isolated from each other, in order that each may be looked at separately. When the slide is heated the grains will be found to adhere to the glass. They may then be studied with the microscope, or if the slide is intended for preservation and future use, it should be gone over carefully under the microscope to see if the particles are sufficiently illustrative, and to reject what is useless from thickness or size. A little Canada balsam should be put over the particles, and the slide should then be heated and finally protected with a thin cover glass as explained on p. 244.

The student by this means is enabled to examine the individual minerals of a rock, and may obtain the most exquisitely perfect crystals whose optical characters, crystallographic forms, inclusions, and intergrowths, he may study as easily as if he had large specimens to handle.

Thin Sections.—To prepare slices of rocks and minerals for the microscope it is not necessary to procure a costly and unwieldy set of apparatus, nor to go through a lengthened course of training. The operation is facilitated, indeed, by the possession of a machine for cutting thin slices, and for reducing and polishing them when mounted on glass. A machine well adapted for both purposes was devised some years ago by Mr. J. B. Jordan, and may be had of Messrs. Cotton and Johnson, Gerrard Street, Soho, London, for £10 : 10s. Another slicing and polishing machine invented by Mr. F. G. Cuttell, 47 Rathbone Place, W., London, costs £6 : 10s. But these machines are rather unwieldy to be carried about the country by a field-geologist. Fuess of Berlin supplies two small and convenient hand-instruments, one for slicing, the other for grinding and polishing. The slicing machine is not quite so satisfactory for hard rocks as one of the larger more solid forms of apparatus worked by a treadle. But the grinding-machine is exceedingly useful, and might be added to a geologist's outfit without material inconvenience. If a lapidary is within reach, much of the more irksome part of the work may be saved by getting him to cut off thin slices. The thickness of each slice must depend greatly upon the nature of the rock, the rule being to make the slice as thin as the rock will allow, so as to save labour in grinding down afterwards.

Excellent rock-sections, however, may be prepared without any machine, provided the operator possesses ordinary neatness of hand and patience. He must procure as thin chips as possible of the rocks he proposes to slice. These he can usually obtain in the field where he is hammering. He should select as fresh a portion of the rock as may be accessible, and by a dexterous use of the hammer break off from a sharp edge a number of thin splinters or chips, out of which he can choose one or more for making into rock-slices. These chips may be about an inch square. It is well to take several of them, as the first specimen may chance to be spoiled in the preparation. The geologist ought also always to carry off a piece of the same block from which his chip is taken, that he may have a specimen of the rock for future reference and comparison. Every such hand-specimen, as well as the chips belonging to it, ought to be wrapped up in paper on the spot where it is obtained, and inside the wrapper or affixed to the specimen, there should be a label or piece of paper with the locality and any notes that may be thought necessary. It can hardly be too frequently reiterated that all such field-notes ought as far as possible to be written down on the ground where the actual facts are before us for examination.

Having obtained his thin slices, either by having them slit with a machine or by detaching with a hammer as thin splinters as possible, the operator may proceed to the preparation of them for the microscope. For this purpose the following simple apparatus is all that is absolutely needful, though if a grinding-machine be added it will save time and labour. If slides of extreme thinness are required, they will be best obtained from a specially trained lapidary or dealer.

List of apparatus for the preparation of thin slices of rocks and minerals for microscopical examination.

1. A cast-iron plate, ¼ inch thick and 9 inches square.
2. Two pieces of plate-glass, 9 inches square.
3. A Water-of-Ayr stone, 6 inches long by 2½ inches broad.
4. Coarse emery (1lb. or so at a time).
5. Fine or flour emery (ditto).
6. Putty powder (1 oz.)
7. Canada balsam. (There is an excellent kind prepared by Rimmington, Bradford, especially for microscopic preparations, and sold in shilling bottles.)
8. A small forceps.
9. Some oblong pieces of common flat window-glass; 2×1 inches is a convenient size.
10. Glasses with ground edges for mounting the slices upon. They may be had at any chemical instrument-maker in different sizes, the commonest being 3×1 inches.
11. Thin covering-glasses, square or round. These are sold by the ounce; ¼ ounce will be sufficient to begin with.
12. A small bottle of spirits of wine.

The first process consists in rubbing down and polishing one side of the chip or slice. We place the chip upon the wheel of the grinding-machine or, failing that, upon the iron plate, with a little coarse emery and water. If the chip is so shaped that it can be conveniently pressed by the finger against the plate and kept there in regular horizontal movement, we may proceed at once to rub it down. If, however, we find a difficulty, from its small size or otherwise, in holding the chip, one side of it may be fastened to the end of a bobbin or other convenient bit of wood by means of a cement formed of three-parts of rosin and one of bees-wax, which is easily softened by heating. A little practice will show that a slow, equable motion with a certain steady pressure is most effectual in producing the desired flatness of surface. When all the roughnesses have been removed, which can be told after the chip has been dipped in water so as to remove the mud and emery, we place the specimen upon the square of plate-glass, and with flour-emery and water continue to rub it down until all the scratches caused by the coarse emery have been removed and a smooth polished surface has been produced. Care should be taken to wash the chip entirely free of any grains of coarse emery before beginning to the polishing on glass. It is desirable also to reserve the glass for polishing only. The emery gets finer and finer the longer it is used, so that by remaining on the plate it may be used many times in succession. Of course the glass itself is worn down, but by using alternately every portion of its surface and on both sides, one plate may be made to last a considerable time. If after drying and examining it carefully, we find the surface of the chip to be polished and free from scratches, we may advance to the next process. But it will often happen that the surface is still finely scratched. In this case we may place the chip upon the Water-of-Ayr stone and with a little water gently rub it to and fro. It should be held quite flat. The Water-of-Ayr stone too should not be allowed to get worn into a hollow, but should be kept quite flat, otherwise we shall lose part of the chip. Some soft rocks, however, will not take an unscratched surface even with the Water-of-Ayr stone. These may be finished with putty-powder, applied with a bit of woollen rag.

The desired flatness and polish having been secured, and all trace of scratches and dirt having been completely removed, we proceed to grind down the opposite side and reduce the chip to the requisite degree of thinness. The first step at this stage is to cement the polished surface of the chip to one of the pieces of common glass. A thin piece of iron (a common shovel does quite well) is heated over a fire, or is placed between two supports over a gas-flame. On this plate must be laid the piece of glass to which the specimen is to be affixed, and the specimen itself. A little Canada balsam is dropped on the centre of the glass and allowed to remain until it has acquired the necessary consistency. To test this condition, the point of a knife should be inserted into the balsam, and on being removed should be rapidly cooled by being pressed against some cold surface. If it soon becomes hard it has been sufficiently heated. Care, however, must be observed not to let it remain too long on the hot plate; for it will then become brittle and start from the glass at some future stage, or at least will break away from the edges of the chip and leave them exposed to the risk of being frayed off. The heat should be kept as moderate as possible, for if it becomes too great it may injure some portions of the rock. Chlorite, for example, is rendered quite opaque if the heat is so great as to drive off its water.

When the balsam is found to be ready, the chip, which has been warmed on the same plate, is lifted with the forceps and its polished side is laid gently down upon the balsam. It is well to let one end touch the balsam first, and then gradually to lower the other, as in this way the air is driven out. With the point of a knife the chip should be moved about a little, so as to expel any bubbles of air and promote a firm cohesion between the glass and the stone. The glass is now removed with the forceps from the plate and put upon the table, and a lead weight or other small heavy object is placed upon the chip, so as to keep it pressed down until the balsam has cooled and hardened. If the operation has been successful the slide ought to be ready for further treatment as soon as the balsam has become cold. If, however, the balsam is still soft, the glass must be again placed on the plate and gently heated, until on cooling the balsam resists the pressure of the finger-nail.

Having now produced a firm union of the chip and the glass, we proceed to rub down the remaining side of the stone with coarse emery on the iron plate as before. If the glass cannot be held in the hand or moved by the simple pressure of the fingers, which usually suffices, it may be fastened to the end of the bobbin with the rosin cement as before. When the chip has thus been reduced until it is tolerably thin, until, for example, light begins to appear through it when held between the eye and the window, we may, as before, wash it clear of the coarse emery and continue the reduction of it on the glass plate with fine emery. Crystalline rocks, such as granite, gneiss, diorite, dolerite, and modern lavas, can be reduced to the required thinness on the glass. Softer rocks may require gentle treatment with the Water-of-Ayr stone.

The last parts of the process are the most delicate of all. We desire to make the section as thin as possible, and for that purpose continue rubbing until after one final attempt we perhaps find to our dismay that great part of the slice has disappeared. The utmost caution must consequently be used. The slide should be kept as flat as possible, and looked at frequently, that the first indications of disruption may be detected. The thinness desirable or attainable depends in great measure upon the nature of the rock. Transparent minerals need not be so much reduced as more opaque ones. Some minerals, indeed, remain absolutely opaque to the last, like pyrite, magnetite, and ilmenite.

The slide is now ready for the microscope. It ought always to be examined with that instrument at this stage. We can thus see whether it is thin enough, and if any chemical tests are required they can readily be applied to the exposed surface of the slice. If the rock has proved to be very brittle, and we have only succeeded in procuring a thin slice after much labour and several failures, nothing further should be done with the preparation unless to cover it with glass, as will be immediately explained, which not only protects it, but adds to its transparency. But where the slice is not so fragile, and will bear removal from its original rough scratched piece of glass, it should be transferred to one of the glass-slides (No. 10). For this purpose the preparation is once more placed on the warm iron plate, and close alongside of it is put the glass-slide, which has been carefully cleaned, and on the middle of which a little Canada balsam has been dropped. The heat gradually loosens the cohesion of the slice, which is then very gently pushed along to the contiguous clean slip of glass. Considerable practice is needed in this part of the work, as the slice, being so thin, is apt to go to pieces in being transferred. A gentle inclination of the warm plate is advantageous, so that a tendency may be given to the slice to slip downwards of itself on to the clean glass. We must never attempt to lift the slice. All shiftings of its position should be performed with the point of a long needle or other sharp instrument. If it goes to pieces we may yet be able to pilot the fragments to their resting-place on the balsam of the new glass, and the resulting slide may be sufficient for the required purpose.

When the slice has been safely conducted to the centre of the glass slip, we put a little Canada balsam over it and allow it to be warmed as before. Then taking with the forceps one of the well-cleaned thin cover-glasses, we allow it gradually to rest upon the slice by letting down first one side, and then by degrees the whole. A few gentle circular movements of the cover-glass with the point of the needle or the forceps may be needed to ensure the total disappearance of air-bubbles. When these do not appear, and, when, as before, we find that the balsam has acquired the proper degree of consistence, the slide containing the slice is removed, and placed on the table with a small lead weight above it in the same way as already described. On becoming quite cold and hard the superabundant balsam round the edge of the cover-glass may be scraped off with a knife, and any which still adheres to the glass may be removed with a little spirits of wine.

Small labels should be kept ready for affixing to the slides to mark the locality and reference number of each specimen. Thus labelled the slide may be put away for future study and comparison.

The whole process seems perhaps a little tedious. But in reality much of it is so mechanical that after the mode of manipulation has been learnt by a little experience, the rubbing down may be done while the operator is reading. Thus in the evening, when enjoying a pleasant book after his day in the field, he may at the same time rub down his rock-chips, and thus get over the drudgery of the operation almost unconsciously.

Boxes with grooved sides for carrying microscopic slides are sold in different sizes. Such boxes are most convenient for field-work, as they go into small space, and with the help of a little cotton-wool they hold the glass-slides firmly without risk of breakage. Cheap card-board trays for the same purpose are made by Y. J. Pentland, 38 West Smithfield, London, and also at Edinburgh, For a final resting-place, a case with shallow trays or drawers in which the slides can lie flat is most convenient.

One final remark may here be required. The learner must not suppose that having prepared his slices, he has nothing to do but to place them under the microscope and at once determine their composition. He will find it by no means an easy task to make satisfactory progress, and at first he may be inclined to abandon microscopic work in despair of ever gaining confidence in it. Let him, however, begin by studying individual minerals, and make himself acquainted gradually with their various characters. He should prepare, after the manner described on p. 227, a series of slides of the minerals which he is most likely to meet with either as principal or as accessory ingredients of rocks. By carefully crushing in a steel mortar a small fragment of such a mineral he will obtain an abundant supply of minute cleavage-flakes which he can wash out and mount as slides for constant study and reference, until he has familiarised himself with the microscopic characters of the minerals, and prepared himself for the recognition of the same minerals as components of rocks. He may also increase his knowledge by obtaining carefully prepared thin slices of charactersitic minerals of each system, cut with reference to the crystallographic axes of the crystals.

By training his eye in the study of such slides he will fit himself for discriminating the minerals as they occur in rocks. But he ought on no account to speak confidently about the microscopic structure of rocks until he feels assured that the confidence arises from sound knowledge, and should specially avoid rushing into print on the subject.

THE MICROSCOPE

As already stated (*ante*, p. 32), it is not necessary to procure an expensive microscope with very high magnifying powers. For most purposes of the field-geologist the 1½-inch objective with a magnifying power of from 20 to 50 or 60 diameters, according to the eye-pieces employed, will be found the most generally useful. But he should also have an objective capable of giving, with suitable eye-piece combinations, magnification up to from 200 to 300 diameters. A nose-piece for both objectives screwed to the foot of the tube saves much time and trouble by enabling the observer at once to pass from a low to a high power. Two Nicol prisms are indispensable; one of these is to be fitted below the stage, the other is most advantageously placed over the eyepiece. A quartz-plate is useful. It should be so arranged as to be conveniently slipped in and out of the field as required. The numerous small pieces of apparatus necessary for physiological work are not needed in the examination of rocks and minerals.

Reflected Light.—It is always desirable to observe the characters of a rock as an opaque object. This cannot usually be done with a broken fragment of the stone, except of course with very low powers. But it may be accomplished by making use of the powder as explained on p. 236. Another method is to place a thin slide of the rock in the field of the microscope, and throwing the mirror out of gear, to converge as strong a light upon it as can be had, short of bright direct sunlight. The advantage of this method is more particularly noticeable in the case of opaque minerals. The sulphides and iron oxides, so abundant in rocks, appear as densely black objects with transmitted light, and show only their external form. But by throwing a strong light upon their surface we may often discover that they possess a distinct and characteristic internal structure. Titaniferous iron is an admirable example of the advantage of this method. Seen with transmitted light that mineral appears in black, utterly structureless grains or opaque patches, though frequently bounded by definite lines and angles. But with reflected light the cleavage and lines of growth of the mineral can often be clearly seen, and what seemed to be uniform black patches are then found in many cases to inclose bright brassy kernels of pyrite.

Transmitted Light.—It is, of course, with the light allowed to pass through the preparèd slides that most of the microscopic examination of minerals and rocks is performed. A little experience will show the learner that in viewing objects in this way he may obtain somewhat different results from two slices of the same rock according to their relative thinness. In the thicker one a certain mineral will appear perhaps brown or almost black, while in the other what is evidently the same mineral may be pale yellow or green, or almost colourless. For many purposes of the petrographer extreme thinness in the slides is necessary.

Dichroism.—Some minerals show a change of colour when a Nicol prism is rotated below them. Hornblende, for example, exhibits a gradation from deep brown to dark yellow—a mineral presenting this change is said to be dichroic. To ascertain the dichroism of any mineral we remove the upper polarising prism and leave only the lower. If as we rotate the latter directly under the stage of the microscope no change of tint can be observed, there is no dichroic mineral present, or at least none which shows dichroism at the angle through which it has been cut. But we may often detect little crystals which offer a lively change of tone as the prism goes round ; these are examples of dichroism. This behaviour may be used to discriminate the mineral constituents of rocks. Thus the two minerals hornblende and augite in many respects resemble each other. They differ in their cleavage angles, but augite remains passive or nearly so while the lower prism is rotated : it is not dichroic, or only very feebly so, while hornblende is strongly dichroic.

Polarised Light.[1]—By means of polarised light an exceedingly delicate method of investigation is made available. But for its adequate use some acquaintance with optics is necessary. For the methods of research reference should be made to the treatises quoted on p. 250.

To examine minerals and rocks in polarised light both the Nicol prisms are employed in their respective places. If the object examined is a piece of glass, or an amorphous body, or a crystal belonging to some substance which crystallises in the regular or cubic system, the light will reach our eye unaffected by the intervention of the object, when the axes of the two prisms are at right angles. The field will remain dark, in the same way as if no intervening object were there. If, however, the substance under examination is a mineral belonging to one of the other crystallographic systems, it will modify the polarised beam of light. On rotating one of the prisms we perceive bands or flashes of colour, and numerous lines appear which before were invisible. The field no longer remains dark when the two Nicol prisms are crossed.

It is evident, therefore, that we may readily tell by this means whether or not a rock contains any glassy constituent. If it does, then that portion of its mass will become dark when the prisms are crossed, while the crystalline parts (except those belonging to the isometric

[1] On this subject the student should consult an elementary treatise such as that of Spottiswood (Macmillan and Co.)

system) will remain conspicuous by their brightness. A thin plate of quartz makes this separation of the glassy and crystalline parts of a rock even more satisfactory. It is placed under the stage, and the Nicol prisms are so adjusted with reference to it that the field of the microscope appears uniformly violet. The glassy portion of any rock placed on the stage will allow the violet light to pass through unchanged, but the crystalline portions will show other prismatic colours. The object should be rotated in the field and the eye kept steadily fixed upon one portion of the slide at a time, so that any change may be observed.

It would be far beyond the compass of this little handbook to enter into the details of the microscopic examination of rocks. The student who desires to pursue the subject further will find the needful assistance in the works quoted below.[1] For his satisfaction in the

[1] Sorby "On the Microscopic Structure of Crystals, indicating the Origin of Minerals and Rocks," *Quart. Journ. Geol. Soc.* xiv., 453; Zirkel's *Mikroskopische Beschaffenheit der Mineralien und Gesteine* (Leipzig, 1873); Rosenbusch's *Mikroskopische Physiographie der Mineralien und Gesteine*, 2 vols., 3d edit. 1892-96. An abridgment of this work in English has been made by Prof. Iddings, and is published by Macmillan and Co.; while the Petrographical Tables have been translated by Dr. F. H. Hatch, and are separately published by Swan, Sonnenschein, and Co.—forming a useful handbook. Other works are Rosenbusch's *Elemente der Gesteinslehre*, 1898; A. Harker's *Petrology for Students* (Cambridge Natural Science Manuals); Rutley's *The Study of Rocks* (Longmans); Cole's *Aids in Practical Geology* (Griffin and Co.), 3d edit. 1898; Hatch's *Introduction to Petrology—Igneous Rocks* (Swan, Sonnenschein, and Co.) An admirable little pamphlet on the use of his improved microscope has been prepared by Mr. A. Dick, and may be had of the makers of the instrument, Swift and Son.

determination of rocks he may propound to himself the following questions :—1st, Is the rock entirely crystalline, consisting solely of crystals of different minerals interlaced ; and if so, what are these minerals ? 2nd, Is there any trace of a glassy ground-mass ? If there is, he may regard the rock as belonging to the volcanic series. 3rd, Can he detect any evidence of the devitrification of what must have been at one time the glassy basis of the whole rock ? This devitrification might be shown by the appearance of numerous microscopic hairs, rods, bundles of feather-like irregular or granular aggregations. 4th, In what order did the minerals crystallise ? This may often be very clearly made out with the microscope, as, for instance, where one mineral is partially or completely inclosed within another. 5th, What is the nature of any alteration which the rock may have undergone ? In a vast number of cases, the slices show abundant evidence of such metamorphism ; felspar passing into granular kaolin, augite changing into various indefinite green products ("viridite"), olivine into serpentine, titaniferous iron into leucoxene, while secondary calcite, quartz, epidote, or zeolites run in minute veins or fill up interstices of the rock. 6th, Is the rock a fragmental one ; and if so, what is the nature of its component grains ? Is any trace of organic structure to be detected ?

In fine, I return once more to the main purpose of this book, which is to induce the reader to cultivate geology as an out-of-door recreation, and to give him a few hints for his guidance. Apart from its healthful mental training as a branch of ordinary education, geology as an open-air pursuit affords an admirable training in habits of observation, furnishes a delightful relief from the cares and routine of everyday life, takes us into the open fields and the free fresh face of nature, leads us into all manner of sequestered nooks, whither hardly any other occupation or interest would be likely to send us, sets before us problems of the highest interest regarding the history of the ground beneath our feet, and thus gives a new charm to scenery which may be already replete with attractions. Even, therefore, should the reader never write a single sentence of geological description, nor venture to put one geological line upon a map, he may gain from the prosecution of field-geology many a happy and profitable hour, alike in the country into which the pursuit leads him, and in his own home with quiet reflection on what he has seen and done in the field.

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THE END

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