II.—*The History of Volcanic Action during the Tertiary Period in the British Isles.*

By ARCHIBALD GEIKIE, LL.D., F.R.S., Director General of the Geological Survey of the United Kingdom. (Plates I., II.)

(Read 21st May 1888.)

CONTENTS.

INTRODUCTION.

Among the problems for the study of which the remarkably varied geology of the British Isles offers peculiar facilities, perhaps none ranks higher in importance or in general interest than the history of volcanic action. Placed on the oceanic border of an ancient continental area, the region of Britain has lain within the limits where hypogene activity is specially prone to manifest itself. From early geological times this activity has been displayed in various characteristic forms. Hence, within the geological records of Britain there has been preserved a more continuous and complete chronicle of volcanic phenomena than, so far as I am aware, has yet been discovered in any tract of similar size on the face of the globe. The rocks of the country have been investigated so long and so minutely that their general chronological succession has been accurately ascertained, and hence the precise horizon of each volcanic episode can be definitely fixed. The varying phases of eruptivity in different geological periods can be made out, and a large body of evidence can thus be amassed bearing on the general question of the past history of volcanism.

Taking the broadest view of the subject, we find that the volcanic history of Britain naturally divides itself into two widely separated periods. The first of these embraces the vast Palæozoic ages; the second falls entirely within older Tertiary time. Between these two periods comes the prolonged interval marked by the whole series of Mesozoic formations in which, save at their base, in the lower Triassic rocks of Devonshire, no trace of contemporaneous volcanic action is known. It is to the records of the second of the two great volcanic eras that the present memoir is devoted.

Before entering upon the detailed investigation, it may be useful to sketch briefly what has been the progress of opinion regarding the phenomena to be discussed. The basaltic cliffs of Antrim and the Inner Hebrides had attracted the notice of passing travellers, and their striking scenery had become more or less familiar to the reading public, before any attention was paid to their remarkable geological structure and history. In particular, the wonders of the Giant's Causeway and the Isle of Staffa had already begun to draw pilgrims, even from distant countries, at a time when geology was still in its earliest infancy. The scientific tourist of those days who might care to look at rocks, was, in most cases, a mineralogist, for whom their structural relations and origin were subjects that lay outside of the range of his knowledge or habits of thought. One of the earliest traces of an intelligent appreciation of some of the geological interest of the region is to be found in WHITEHURST'S *Inquiry into the Original State and Formation of the Earth* (2nd edit., 1786), where a good account of the basalt-cliffs of Antrim is given, and where the basaltic rocks are regarded as the results of successive outflows of lava from some centre now submerged beneath the Atlantic. More important are the observations contained in two letters of ABRAHAM MILLS, published in the *Philosophical Transactions* for 1790. This writer had been struck with the dykes on the north coast of Ireland, and was led to examine also those in some of the nearer Scottish islands. He believed them to be of truly volcanic origin, and spoke of them as veins of lava. A few years later, FAUJAS ST FOND made his well-known pilgrimage to the Western Isles. Familiar with the volcanic rocks of the Continent, he at once recognised the volcanic origin of the basalts of Mull, Staffa, and the adjoining islands. His *Voyage*, published in Paris in 1797, may be taken as the beginning of the voluminous geological literature which has since gathered round the subject. Three years afterwards (1800) appeared JAMESON'S

Outline of the Mineralogy of the Scottish Isles. Fresh from the teaching of WERNER at Freiberg, the future distinguished Professor of Natural History in the Edinburgh University naturally saw everything in the peculiar Wernerian light. He gave the first detailed enumeration of some of the eruptive rocks of the Hebrides, but of course ridiculed the idea of their igneous origin. Having heard of a reported "crater of a volcano" near Portree, he ironically expressed a hope that "probably there may be still sufficient heat to revive the spirits of some forlorn fire-philosopher, as he wanders through this cold, bleak country."

The advent of JAMESON to Edinburgh gave a fresh impetus to the warfare of the Plutonists and Neptunists, for he brought to the ranks of the latter a mineralogical skill such as none of their Scottish opponents could boast. The igneous origin of basalt, which the Plutonists stoutly maintained, was as strongly denied by the other side. For some years one of the most telling arguments against the followers of HUTTON was derived from the alleged occurrence of fossil shells in the basalt of the north coast of Ireland. KIRWAN, whose *Essays* appeared in 1799, quoted with evident satisfaction RICHARDSON's observation of "shells in the basalt of Ballycastle," and RICHARDSON himself, though the true explanation that the supposed basalt is only Lias shale altered by basalt, had been given in 1802, by PLAYFAIR, in his *Illustrations of the Huttonian Theory,* continued for ten years afterwards to reiterate his belief in the aqueous origin of basalt. Thus the Tertiary volcanic rocks furnished effective weapons to the combatants on both sides. The dispute regarding the black fossiliferous rocks of Portrush had the effect of drawing special attention to the geology of the north of Ireland. Among the more noted geologists who were led to examine them, particular reference must be made to CONYBEARE and BUCKLAND, who, in the year 1813, studied the interesting coast-sections of Antrim. The report of their observations gives an excellent summary of the arguments for the truly igneous origin of basalt, and a statement of opinion in favour of the view that the bedded basalts are the products of submarine volcanoes. BERGER also about the same time described in fuller detail the geology of the Antrim district, and showed the rocks of the basalt-plateau to be younger than the Chalk. He likewise made a study of the basalt-dykes of the north of Ireland, and was the first to point out their prevalent north-westerly direction. These memoirs, contained in the third volume of the *Transactions of the Geological Society,* may justly be regarded, to quote the words of PORTLOCK, as "the first effectual step made in Irish geology." PORTLOCK's own *Report on Londonderry,* published in 1843, is still the most complete summary of information regarding the geology of that interesting region.

While such advances were being made in the knowledge of the structure of the volcanic rocks of the north of Ireland, the geologist had already appeared who was the first to attempt a systematic examination of the Western Islands, and whose published descriptions are still the chief source of information regarding the geology of this extensive region. Dr MACCULLOCH seems to have made his first explorations among the Hebrides some time previous to the year 1814, for in that year there were published, in the second volume of the *Transactions of the Geological Society*, some remarks by him on specimens from that district transmitted to the Society. For several years in succession he devoted himself with great energy and enthusiasm to the self-imposed task of geologically examining and mapping all the islands that lie to the westward of Scotland, from the remote St Kilda even as far as the Isle of Man. From time to time, notices of parts of his work were given in the *Transactions of the Geological Society.* But eventually in 1819 he embodied the whole in his *Description of the Western Islands of Scotland.*

This great classic marks a notable epoch in British geology. Properly to estimate its value, we should try to realise what was the state of the science in this country at the time of its appearance. So laborious a collection of facts, and so courageous a resolution to avoid theorising about them, gave to his volumes an altogether unique character. His descriptions were at once adopted as part of the familiar literature of geology. His sections and sketches were reproduced in endless treatises and text-books. Few single works of descriptive geology have ever done so much to advance the progress of the science in this country. With regard to the special subject of the present memoir, MACCULLOCH showed that the basalts and other eruptive rocks of the Inner Hebrides pierce and overlie the Secondary strata of these islands, and must therefore be of younger date. But though he distinguished the three great series of "trap-rocks," "syenites" and "hypersthene-rocks" or "augite-rocks," and indicated approximately their respective areas, he did not attempt to unravel their relations to each other. Nor did he venture upon any speculations as to the probable conditions under which these rocks were produced. He claimed that those who might follow him would find a great deal which he had not described, but little that he had not examined. Subsequent observers have noted many important facts, of which, had he observed them, he would at once have seen the meaning, and which he certainly would not have passed over in silence. But as a first broad outline of the subject, MACCULLOCH's work possesses a great value, which is not lessened by the subsequent discovery of details that escaped his notice, and of points of geological structure which he failed to discover.

It may here be remarked, that among the earliest and ablest observations of the volcanic rocks of this country were those made by foreigners. In some cases, students who had repaired from abroad to Edinburgh for education caught the geological enthusiasm then so marked in this city, and made numerous journeys through the country in search of further knowledge of its rocks and minerals. In other instances, geologists of established reputation, attracted by the interest which the published accounts of Scottish geology had excited, were led to visit the country and to record their impressions of its rock-structure. Of the first class of observers the two most noted were AMI BOUÉ and L. A. NECKER. BOUÉ took his degree of M.D. at Edinburgh in 1816. During his stay in Scotland he made extensive tours across the kingdom, and acquired a wide knowledge of its rocks and minerals. In the year 1820 he published his *Essai géologique sur l'Ecosse.* The value of this work as an original contribution to the geology of the British Isles has probably never been adequately acknowledged. For this want of due recognition the author himself was no doubt in some measure to blame. He refers distinctly enough to various previous writers, notably to JAMESON and MACCULLOCH, but he modestly mingles the results of his own personal examinations with theirs in such a way that it is hardly possible to ascertain what portions are the outcome of his own original observations. Less credit has accordingly been given to him than he could fairly have claimed for solid additions to the subjects of which he treated. In the later years of his life, I had opportunities of learning personally from him how extensive had been his early peregrinations in Scotland, and how vivid were the recollections which, after the lapse of half a century, he still retained of them. Judged simply as a well-ordered summary of all the known facts regarding the geology of Scotland, his *Essai* must be regarded as a work of very great value. Especially important is his arrangement of the volcanic phenomena of Scotland, which stands far in advance of anything of the kind previously attempted. Under the head of the "Terrain Volcanique," he treats of the basaltic formations, distinguishing them as sheets (*nappes, coulées*) and dykes; and of the felspathic or trachytic formations which he subdivides into phonolites, trachytes, porphyries (forming mountains and also sheets), and felspathic or trachytic dykes. In the details supplied under each of these sections he gives facts and deductions which were obviously the result of his own independent examination of the ground, and he likewise marshals the data accumulated by JAMESON, MACCULLOCH, and others in such a way as to present a comprehensive and definite picture of the volcanic phenomena of Scotland such as no previous writer had ventured to give.

L. A. NECKER, as the grandson of the illustrious DE SAUSSURE, had strong claims on the friendly assistance of the Edinburgh School of Geology when he went thither in 1806, at the age of twenty, to prosecute his studies. He was equally well received by the Plutonists and Neptunists, and devoted much time to the exploration of the geology, not only of the Lowlands, but of the Highlands and the Inner Hebrides. Most of his observations appear to have been made in the year 1807, but it was not until fourteen years afterwards that he published his *Voyage en Ecosse et aux Iles Hebrides.** The geological part of this work must be admitted to be somewhat disappointing. The author's caution not to commit himself to either side of the geological controversy then waging, makes his descriptions and explanations rather colourless. He adds little to what was previously known, and even as regards the true volcanic origin of the basalts of the Western Islands he could not make up his mind, contenting himself by referring them to "the trappean formation." But these islands had so fascinated him that eventually he returned to them as his adopted home, passed the last twenty years of his life among them, and died and was buried there. Besides his *Voyage*, he published in French an account of the dykes of the Island of Arran which appeared in vol. xiv. of the *Transactions* of this Society.

* See biographical notice of L. A. Necker, by Principal J. D. Forbes, *Proc. Roy. Soc. Edin.*, v. (1862) p. 53.

Among the foreign geologists who have been drawn to the mountains and islands of Scotland by the interest of its rocks, I have already alluded to FAUJAS ST FOND. Much more important, however, were the observations made some thirty years later by two German men of science, VON OYENHAUSEN and VON DECHEN. Their careful descriptions of the geology of Skye, Eigg, and Arran added new materials to the knowledge already acquired by native geologists.* To some of the more interesting parts of their work, reference will be made in later parts of this memoir.

The numerous trap-dykes of Northumberland, Durham, and Northern Yorkshire at an early date attracted the attention of geologists. As far back as 1817, they had been the subject of a memoir by N. J. WINCH, who gave an account of their effects on the adjacent rocks. More important were the subsequent papers on the same subject by SEDGWICK, who, discussing the lithological characters, probable origin, and geological age of the dykes, pointed out that while the Cleveland dyke was undoubtedly younger than a large part of the Jurassic rocks, there was no direct evidence to determine whether the dykes farther north were earlier or later than the time of the Magnesian Limestone. Subsequent accounts of the dykes of the same region were given by BUDDLE,† M. FORSTER,‡ N. WOOD,§ H. T. M. WITHAM,‖ TATE,¶ and others, while in more recent years important additions to our knowledge of these dykes and of their effects have been made by Sir J. LOWTHIAN BELL** and Mr J. J. H. TEALL.††

The geological age of the great series of Tertiary volcanic rocks has only been determined, district by district, and at wide intervals. That some part of the Antrim basalts are younger than the Chalk of that region was clearly shown by BERGER, CONYBEARE, and BUCKLAND. PORTLOCK, however, in his *Report on Londonderry*, &c., referred to the occurrence of detached blocks of basalt which he supposed to be immersed in the Chalk near Portrush, and which inclined him to believe that "the basaltic flows commenced at a remote period of the Cretaceous system." MACCULLOCH showed that the corresponding basaltic plateaux of the Inner Hebrides were certainly younger than the Oolitic rocks of that region. But no nearer approximation to their date had yet been made. In the year 1850 the DUKE OF ARGYLL announced the discovery of strata containing fossiliferous chalk-flints and dicotyledonous leaves, lying between the bedded basalts of Ardtun Head, in the Isle of Mull.‡‡ In the following year these fossil leaves were described by EDWARD FORBES, who regarded them as decidedly Tertiary, and most probably Miocene. This was the first palæontological evidence for the determination of the geological age of any portion of the basalt-plateaux, and it indicated that the basalts of the south-west of Mull were of older Tertiary date. Taken also in connection with the occurrence of lignite-beds between the basalts of Antrim, it proved that these volcanic plateaux were not due to submarine eruptions, as the earlier geologists had

* Karsten's *Archiv* (1829), vol. i. p. 56.

† *Trans. Nat. Hist. Soc. Northumberland*, i. (1831) p. 9.

‡ *Op. cit.*, i. p. 44.

§ *Op. cit.*, i. pp. 305, 306, 308, 309.

‖ *Op. cit.*, ii. (1838) p. 343.

¶ *Trans. Northumberland and Durham*, ii. (1868) p. 30.

** *Proc. Roy. Soc.*, xxiii. (1875) p. 543.

†† *Quart. Jour. Geol. Soc.*, xl. (1884) p. 209.

‡‡ *Brit. Assoc. Report*, 1850, sections, p. 70, and *Quart. Jour. Geol. Soc.*, vii. (1851) p. 87.

supposed, but pointed to the subærial outpouring of lava at successive intervals, during which terrestial vegetation sprang up upon the older outflows.

While FORBES brought forward palæontological proofs of the Tertiary age of the volcanic rocks of the south-west of Mull, he at the same time laid before the Geological Society a paper on the Estuary Beds and the Oxford Clay of Loch Staffin, in Skye, wherein, while admitting the existence of appearances which might be regarded as favourable to the view that the intercalated basalts of that region were of much later date than the Oolitic strata between which they might have been intrusively injected, he stated his own belief that they were really contemporaneous with the associated stratified rocks, and thus marked an outbreak of volcanic energy at the close of the Middle Oolitic period.* The DUKE OF ARGYLL, in the paper which he on the same occasion communicated to the Geological Society, adopted this view of the probable age of most of the basalts of the Western Islands. He looked upon the Tertiary volcanic rocks of Mull as occupying a restricted area, the great mass of the basalt of that island, like that of Skye, being regarded by him as probably not later than some part of the Secondary period.

It must be granted that the appearances of contemporaneous intercalation of the basalt among the Secondary strata are singularly deceptive. When, several years after the announcement of the Tertiary age of the basalts of Ardtun, I began my geological work in the Inner Hebrides, I was led to the same conclusion as EDWARD FORBES, and expressed it in an early paper, read before this Society in 1861, on the "Chronology of the Trap-rocks of Scotland."† All over the north of Skye I traced what appeared to be evidence of the contemporaneous interstratification of basalts with the Jurassic rocks, and I concluded (though with some reservation) that the whole of the vast basaltic plateaux of that island were not younger than some later part of the Jurassic period. In that paper the attention of geologists was called to the probable connection of the great system of east-and-west dykes traversing Scotland and the north of England, with the basalt-plateaux of the Inner Hebrides, and as I believed the latter to be probably of the age of the Oolitic rocks, I assigned the dykes to the same period in geological history. But subsequent explorations enabled me to correct the mistake into which, with other geologists, I had fallen regarding the age of the volcanic phenomena of the Western Islands. In 1867 I showed that, instead of being confined to a mere corner of Mull, the Tertiary basalts, with younger associated trachytic or granitic rocks, covered nearly the whole of that island, and that in all likelihood the long chain of basaltic masses, extending from the north of Ireland along the west coast of Scotland to the Faroe Islands, and beyond these to Iceland, was all erupted during the Tertiary period. At the same time I drew special attention to the system of east-and-west dykes as proofs of the vigour of volcanic action at that period, and I furnished evidence that this action was prolonged through a vast interval of time, during which great subærial denudation of the older lavas took place before the outflow of the younger.‡ Later, in the same year, in

* *Quart. Jour. Geol. Soc.*, vol. vii. (1851) p. 104.

† *Trans. Roy. Soc. Edin.*, xxii. (1861) p. 649.

‡ *Proc. Roy. Soc. Edin.*, vi. (1867) p. 71.

an address to the Geological Section of the British Association, I reiterated these views, and more particularly emphasised the importance of the system of dykes, which in my opinion was possibly the most striking manifestation of the vigour of Tertiary volcanic action.* In 1871, after further explorations in the field, I gave a detailed account of the structure which had led to the mistake as to the age of the Tertiary volcanic rocks of the Western Islands; and in a description of the island of Eigg, I brought forward data to show the enormous duration of the Tertiary volcanic period in the west of Britain.† It was my intention that the paper in which these views were enunciated should be continued in a subsequent series of memoirs. Before the preparation of the second of the series was completed, Mr J. W. JUDD read before the Geological Society (21st January 1874) a paper "On the Ancient Volcanoes of the Highlands."‡ The most novel feature of this paper was the announcement that the author had recognised the basal wrecks of five great central volcanoes in the Western Islands, among which that of Mull was inferred by him to have been at least 14,500 feet high. He was led to the conclusion that the volcanic period in these regions was divisible into three sections,—the first marked by the outburst of acid rocks (felspathic lavas and ashes, connected with deeper and more central granitic masses); the second by the extrusion of basic lavas and tuffs (the basaltic plateaux); the third by the appearance of small sporadic volcanic cones ("felspathic, basaltic, or intermediate in composition") after the great central cones had become extinct. It will be seen from the present communication that the views adopted by Professor JUDD are not those to which my study of the subject has led me. I have not been able to discover evidence of any great central volcanoes, and have found the order of outflow of the successive groups of rocks to have been the reverse of what he believed it to be. The appearance of his memoir, however, led me to postpone the continuation of the series of papers which I had begun. The conviction that, in some way or other, as yet wholly inexplicable to me, the dykes, which at so early a period of my researches arrested my attention, had played a leading part in the volcanic phenomena of the Tertiary period, became every year stronger. At last, in the year 1879, during a traverse of some portions of the volcanic region of Wyoming, Montana, and Utah, I was led to perceive the meaning of what had hitherto been so puzzling. Riding over those great plains of basalt, and looking at the sections cut by the rivers through the thick series of horizontal basalt-beds underlying them, I appreciated for the first time the significance of RICHTHOFEN'S views regarding "massive" or "fissure-eruptions," as contradistinguished from those of central volcanoes like Etna or Vesuvius, and I saw how completely the structure and history of these tracts of Western America explain those of the basalt-plateaux of Britain.§ Since that year, at such intervals of leisure as I could command, I have renewed the investigation, and now at last, after a quarter of a century of more or less continuous labour in the

* *Brit. Assoc. Report* (Dundee), 1867, sects. p. 49.

† *Quart. Jour. Geol. Soc.*, xxvii. (1871) p. 279.

‡ *Quart. Jour. Geol. Soc.*, xxx. (1874) p. 220.

§ *Geological Essays at Home and Abroad*, pp. 271, 274; *Nature*, November 1880.

subject, I offer my results to the Royal Society of Edinburgh, which honoured and encouraged me by printing in its *Transactions* my first essay on the volcanic rocks of this country.

In describing the geological history of a great series of rocks, chronological order is usually the most convenient method of treatment. Where, however, the rocks are of volcanic origin, and do not always precisely indicate their relative age, and where moreover the same kinds of rock may appear on widely separated geological horizons, it is not always possible or desirable to adhere to the strict order of sequence. With this necessary latitude, I propose to follow the chronological succession from the older to the newer portions of the series. I shall treat first of the system of basic dykes, by which so large a part of Scotland and of the north of England and Ireland is traversed. Many of the dykes are undoubtedly among the youngest members of the volcanic series, and in no case can their age be determined except relatively to the antiquity of the rocks which they traverse. They must, of course, be posterior to these rocks, and hence it would be quite logical to reserve them for discussion at the very end of the whole volcanic phenomena. My reason for taking them at the beginning will be apparent in the sequel. After the dykes, I shall describe the great volcanic plateaux which, in spite of vast denudation, still survive in extensive fragments in Antrim and the Inner Hebrides. The eruptive bosses of basic rocks that have broken through the plateaux will next be discussed. An account will then be given of the protrusions of acid rocks which mark the latest phase of eruption in the region. The last section of the memoir will contain a summary of the history of Tertiary volcanic action in Britain.

I. THE BASIC DYKES.

If a geologist were asked to select that feature in the volcanic geology of the British Isles which more than any other marks this region off from the rest of the European area, he would probably choose the remarkable system of wall-like masses of erupted igneous rock to which the old Saxon word "dykes" has been affixed. From the moors of eastern Yorkshire to the Perthshire Highlands, and from the basins of the Forth and Tay to the west of Donegal and the far headlands of the Hebrides, the country is ribbed across with these singular protrusions to such an extent that it may be regarded as a typical region for the study of the phenomena of dykes. That all the dykes in this wide tract of country are of Tertiary age, I am far from believing. Some of them are of the era of the Old Red Sandstone, others are undoubtedly Carboniferous, while some, though later than the Coal Measures, may be older than the Permian, or at least the Trias formations. As illustrations of these older dykes, I may refer to the remarkable series which traverses the Carboniferous rocks of Northumberland and Durham, and which includes the well-known Whin Sill. That this series belongs to a totally different and greatly more ancient period of extrusion was indicated many years ago by SEDGWICK,* who referred to the previous

* *Trans. Cambridge Phil. Soc.* (1822), vol. ii. p. 23; Winch, *Geol. Trans.*, iv. (1814) p. 25.

observations of WINCH that these dykes, though they ascend through the Coal Measures, never enter the Magnesian Limestone. They differ also in direction from the younger dykes, their general trend being south-westerly. They are further distinguished by petrographical characters.

But when these and all other dykes which can reasonably be referred to older geological periods are excluded, there remains a large majority which cannot be so referred, but which are connected together by various kinds of evidence into one great system that must be of late geological date, and can be assigned to no other than the Tertiary period in the volcanic history of Britain. In my original memoir, "On the Chronology of the Trap-rocks of Scotland," where I first drew attention to this great system of dykes in connection with the progress of volcanic action in the country, I pointed out the grounds on which it seemed to me that these rocks belonged to a comparatively late geological date. My own subsequent experience and the full details of structure collected by my colleagues of the Geological Survey in all parts of the country, have amply confirmed this view, though, as already stated, instead of placing the era of eruption in the Jurassic, I now put it in the older part of the Tertiary period. The characters which link this great series of dykes together as one connected system of late geological date are briefly enumerated in the following list, and will be more fully discussed in later pages.

1. The prevalent tendency of the dykes to take a north-westerly or westerly course. There are exceptions to this normal trend, especially where the dykes are small and locally numerous; but it remains singularly characteristic over the whole region.

2. The increasing abundance of the dykes as they are traced to the west coast and the line of the great Tertiary volcanic plateaux of Antrim and the Inner Hebrides.

3. The rectilinear direction so characteristic of them and so different from the tortuous course of other groups of dykes. The exceptions to this normal feature are as a rule confined to the same localities where departures from the prevalent westerly trend occur.

4. The great breadth of the larger dykes of the system and their persistence for long distances. This is one of their most remarkable and distinctive characters.

5. The posteriority of the dykes to the rest of the geological structure of the regions which they traverse. They are not only younger than the other rocks, but younger than nearly all the folds and faults by which the rocks are affected.

6. The manner in which they cut the Jurassic, Cretaceous, and older Tertiary strata in the districts through which they run. At the south-eastern end of the region they rise through the Lias and Oolite formations, in the west they intersect the Chalk and the Tertiary volcanic plateaux with their later eruptive bosses.

7. Their petrographical characters, among which perhaps the most distinctive is the frequent appearance of the original glassy magma of the plagioclase-pyroxene-magnetite (olivine) rock, of which they essentially consist. This glass, or its more or less completely devitrified representative, often still recognisable with the microscope among the individualised microlites and crystals throughout the body of a dyke, is also not

infrequent as a black vitreous varnish-like coating on the outer walls, and occasionally appears in strings and veins even in the centre.

It is the assemblage of dykes presenting these features which I propose to describe. Obviously, the age of each particular dyke can only be fixed relatively for itself. But when this remarkable community of characters is considered, and when the Tertiary age of at least a very large number of the dykes can be demonstrated, the inference is reasonable that the whole assemblage constitutes one great system, extravasated during a time of great volcanic disturbance, which could not have been earlier than the beginning of the Tertiary period. And this inference may be maintained even when we frankly admit that every dyke within the region is by no means claimed as belonging to the Tertiary series.

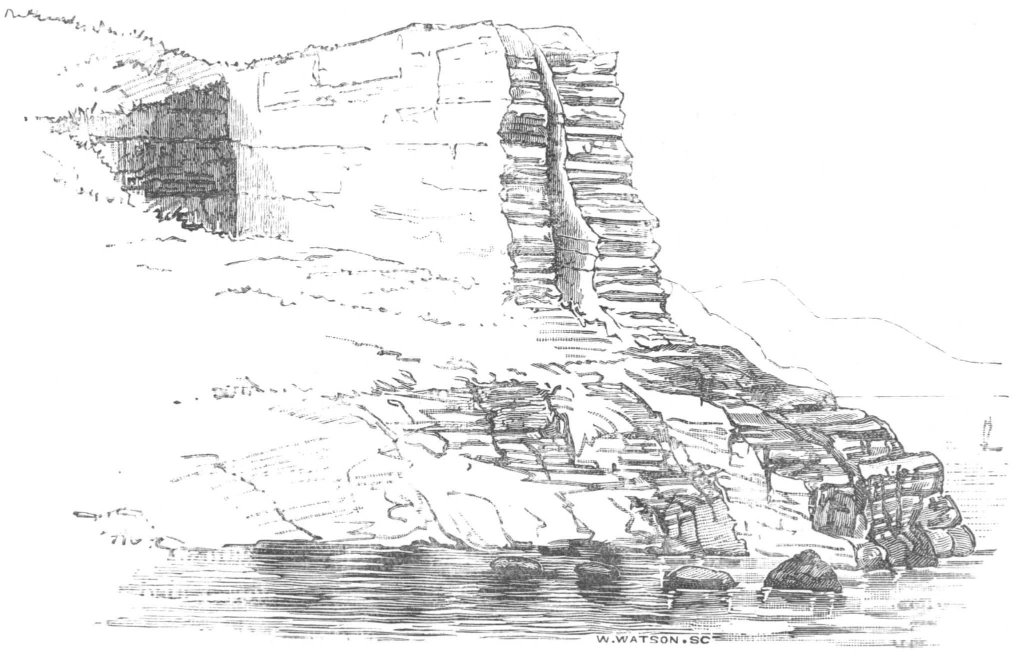


FIG. 1.—Dyke on the south-east coast of the Island of Mull.

In spite of their number and the extraordinary volcanic activity to which they bear witness, the basic dykes form a much less prominent feature in the landscape than might have been anticipated. In the lowlands of the interior, they have for the most part been concealed under a cover of superficial accumulations, though in the water-courses they not infrequently project as hard rocky barriers across the channels, and occasionally form picturesque waterfalls. On the barer uplands, they protrude in lines of broken crag and scattered boulders, which by their decay give rise to a better soil covered by a greener vegetation than that of the surrounding brown moorland. Among the Highland hills, they are often traceable from a distance as long black ribs that project from the naked faces of crag and corry. Along the sea coast, their peculiarities of scenery are effectively displayed. Where they consist of a close-grained rock, they often rise from the beach as straight walls which, with a strangely artificial look, mount into the face of the cliffs on the one side, and project in long black reefs into the sea on the other (fig. 1). Every visitor to the islands of the Clyde will remember how conspicuous such features are there. But it is among the Inner Hebrides that this kind of scenery is to be found in greatest perfection. The soft dark Lias shales of the island of Pabba, for example, are ribbed across with scores of dykes which strike boldly out to sea. Where, on the other hand, the material of the dykes is coarse in grain, or is otherwise more susceptible to the disintegrating influences of the weather, it has rotted away and left yawning clefts behind, the vertical walls of which are those of the fissures up which the molten rock ascended. Some good instances of this kind are well known to summer visitors on the eastern shores of Arran. Others, on a large scale, may be seen in the interior of the same island along the crests of the granite ridges, and still more conspicuously on the jagged summits of Blath Beinn and the Cuillin Hills of Skye.

§ 1. Geographical Distribution.

The limits of the region within which the dykes occur cannot be very precisely fixed. There can be no doubt, however, that on their southern side they reach to the Cleveland Hills of Yorkshire and the southern borders of Lancashire, and on the northern side to the farther shores of the island of Lewis—a direct distance of 360 miles. They stretch across the basin of the North Sea, including the Isle of Man, and appear in the north of Ireland north of a line drawn from Dundalk Bay to the Bays of Sligo and Donegal. Dykes are of frequent occurrence over the north of England and south of Scotland, at least as far north as a line drawn from the coast of Kincardineshire along the southern flank of the Grampian Hills by the head of Glen Shee and Loch Tay to the north-western coast of Argyleshire. They abound all along the line of the Inner Hebrides and the adjacent coasts of the mainland from the remoter headlands of Skye to the shores of county Louth. They traverse also the chain of the Long Island in the Outer Hebrides. So far as I am aware, they are either absent or extremely rare in the Highlands north of the line I have indicated. But a good many have been found by my colleagues in the course of the Geological Survey of the northern lowlands of Aberdeenshire and Banffshire. The longest of these has been traced by Mr L. Hinxman for rather more than two miles running in a nearly east and west direction through the Old Red Sandstone of Strathbogie, with an average width of about 35 feet. Another in the same district has a width of from 45 to 90 feet, and has been followed for a third of a mile. But far beyond these northern examples, I have found a number of narrow basalt-veins traversing the Old Red flagstones of the Mainland of Orkney, which I have little doubt are also a prolongation of the same late series. Taking, however, only those western and southern districts in which the younger dykes form a notable feature in the geology, we find that the dyke-region embraces an area of upwards of 40,000 square miles—that is, a territory greater than either Scotland or Ireland, and equal to more than a third of the total land-surface of the British Isles (Plate I.).

Of this extensive region the greater portion has now been mapped in detail by the Geological Survey. Every known dyke has been traced, and the appearances it presents at the surface have been recorded. We are accordingly now in possession of a larger body of evidence than has ever before been available for the discussion of this remarkable feature in the geology of the British Isles. I have made use of this detailed information, and besides the data accumulated in my own note-books, I have availed myself of those of my colleagues in the Survey, for which due acknowledgment is made where they are cited.

§ 2. Two Types of Protrusion.

The dykes are far from being equally distributed over the wide region within which they occur. In certain limited areas they are crowded together, a score or more occurring in a single square mile, while elsewhere they appear only at intervals of several miles. Viewed in a broad way, they may be conveniently grouped in two types, which, though no hard line can be drawn between them, nevertheless probably point to two more or less distinct phases of volcanic action. In the first, which for the sake of distinction we may term the Solitary type, there is either a single dyke separated from its nearest neighbours by miles of intervening and entirely dykeless ground, or a group of two or more running parallel to each other, but sometimes a mile or more apart. The rock of which they consist is, on the whole, less basic than in the second type; it includes the andesitic varieties. It is to this type that the great dykes of the north of England and the south and centre of Scotland belong. The Cleveland dyke, for example, at its eastern end has no known dyke near it for many miles. The coal-field of Scotland is traversed by five main dykes, which run in a general sense parallel to each other, with intervals of from half a mile to nearly five miles between them. Dykes of this type display most conspicuously the essential characters of the dyke-structure, in particular the vertical marginal walls, the parallelism of their sides, their great length, and their persistence in the same line.

In the second, or what for brevity may be called the Gregarious type, the dykes occur in great abundance within a particular district. They are on the whole narrower, shorter, less strikingly rectilinear, more frequently tortuous and vein-like, and, on the whole, more basic in composition than those of the first type. They include the true basalts and dolerites. Illustrative districts for dykes of this class are the islands of Arran, Mull, Eigg, and Skye.

The great single or solitary dykes may be observed to increase in number, though very irregularly, from south to north, and also in central Scotland from east to west. They are specially abundant in the tract from the Firth of Clyde along a belt of country some thirty miles broad on either side of the Highland line, as far at least as the valley of the Tay. They form also a prominent feature in the islands of Jura and Islay. Those of the gregarious type are abundantly and characteristically displayed in the basin of the Firth of Clyde. Their development in Arran formed the subject of an interesting paper by NECKER, who catalogued and described 149 of them, and estimated their total number in the whole island to be about 1500.* As the area of Arran is 165 square miles, there would be, according to this computation, about nine dykes to every square mile. But they are far from being uniformly distributed. While appearing only rarely in many inland tracts, they are crowded together along the shore, particularly at the south end of the island, where the number in each square mile must far exceed the average just given. The portion of Argyleshire, between the hollow of Loch Long and the Firth of Clyde on the east and Loch Fyne on the west, has recently been found by my colleague, Mr C. T. CLOUGH, to contain an extraordinary number of dykes (see fig. 17). The coast line of Renfrewshire and Ayrshire shows that the same feature is prolonged into the eastern side of the basin of the Clyde estuary. But immediately to the westward of this area the crowded dykes disappear from the basin of Loch Fyne. In Cantire their scarcity is as remarkable as their abundance in Cowal. Both in the north of Ireland and through the Inner Hebrides, dykes are singularly abundant in and around, but particularly beneath, the great plateaux of basalt. Their profusion in Skye was described early in this century by MACCULLOCH, who called attention more especially to their extraordinary development in the district of Strathaird. "They nearly equal in some places," he says, "when collectively measured, the stratified rock through which they pass. I have counted six or eight in the space of fifty yards, of which the collective dimensions could not be less than sixty or seventy feet." He supposed that it would not be an excessive estimate to regard the igneous rock as amounting to one-tenth of the breadth of the strata which it cuts.†

Among the districts where dykes of the gregarious type abound at a distance from any of the basalt-plateaux, reference should be made to the curious isolated tract of the central granite core of Western Donegal. In that area a considerable number of dykes rises through the granite, to which they are almost wholly confined. Again, far to the east another limited district, where dykes are crowded together, lies among the Mourne Mountains. These granite hills are probably to be classed with those of Arran, as portions of a series of granite protrusions belonging to a far more recent period than that to which the youngest granitic masses of the Highlands are to be assigned.

Though the dykes may be conveniently grouped in two series or types, which on the whole are tolerably well marked, it is not always practicable to draw any line between them, or to say to which group a particular dyke should be assigned. In some districts, however, in which they are both developed, we can separate them without difficulty. In the Argyleshire region above referred to, for example, which Mr CLOUGH has mapped, he finds that the abundant dykes belonging to the gregarious type run in a general N.W. or N.N.W. direction, and distinctly intersect the much scarcer and less basic dykes of the solitary type, which here run nearly E. and W. (fig. 17). Hence, besides their composition, distinction in number, breadth, rectilinearity, and persistence, the two series demonstrably belong to distinct periods of eruption.

* *Trans. Roy. Soc. Edin.*, xiv. (1840) p. 677.

† *Trans. Geol. Soc.*, iii. (1815) p. 79.

§ 3. NATURE OF COMPONENT ROCKS.

The Tertiary dykes of Britain include representatives of two very distinct groups of igneous rocks. The vast majority of them are basic compounds, belonging to the family of the pyroxenic lavas, which, where the percentage of silica is relatively high, are known as andesites, and where it is relatively low, have been variously styled basalts, dolerites, melaphyres, or diabases. It is to these basic dykes that the general descriptions of the present section exclusively refer. The second class is composed of an acid rock, either more or less crystalline, such as felsite, quartz-porphyry, rhyolite or trachyte; or vitreous, in the form of pitchstone. These acid dykes or veins, though extremely abundant at a few localities, are on the whole rare. They will be described by themselves in subsequent pages (p. 175).

To the field geologist, who has merely their external features to guide him, the ordinary Tertiary basic dykes present a striking uniformity in general petrographical character. They vary indeed in fineness or coarseness of texture, in the presence or absence of porphyritic crystals, amygdules, glassy portions, and other points of structure. But there is seldom any difficulty in perceiving that they are basic rocks belonging to one or other of the types of the basalts, dolerites, diabases, or andesites. This sameness of composition, traceable from Yorkshire to Skye and from Donegal to Perthshire, is one of the strongest arguments for referring this system of dykes to one geological period. At the same time, there are enough of minor variations and local peculiarities to afford abundant exercise for the observing faculties alike in the field and in the study, and to offer materials for arriving at some positive conclusions regarding the geological processes involved in the uprise of the dykes.

1. *External Characters.*—As regards the grain of the rock, every gradation may be found, from a coarsely crystalline mass, in which the component minerals are distinctly traceable with the naked eye, to a black lustrous basalt-glass. Each dyke generally preserves the same character throughout its extent. As a rule, broad and long dykes are coarser in grain than narrow and short ones. For the most part, there runs alongside each side of a dyke a selvage of finer grain than the rest of the mass. This marginal strip varies in breadth from an inch or less up to a foot or more, and obviously owes its origin to the more rapid chilling of the molten rock along the walls of the fissure. It usually shades away imperceptibly into the larger-grained inner portion. Even with the naked eye, its component materials can be seen to be more finely crystalline than the rest of the dyke, though where dispersed porphyritic felspars occur they are usually as large in the marginal strip as in any other part of a dyke.

This finer-grained external band, so distinctive of an eruptive and injected rock, is of great service in enabling us to trace dykes when they traverse other dykes or masses of igneous rock of similar characters to their own. When one dyke crosses another, that which has its marginal band of finer grain unbroken must obviously be the younger of the two.

But in many examples in the south of Scotland, Argyleshire, and the Inner Hebrides, the fineness of grain of the outer band culminates in a perfect volcanic glass. Where this occurs, the glass is usually jet black, more rarely greenish or bluish black in tint, and varies in thickness from about half an inch to a mere varnish-like film on the outer face of the dyke, the average width being probably less than a quarter of an inch. On their weathered surface, these external glassy layers, generally present a pattern of rounded or polygonal prominences, varying up to four or five lines or even more in diameter, and separated by depressions or narrow ribs that remind us of the lines seen in perlitic structure. The transition from the glass to the crystalline part of the marginal fine-grained strip is usually somewhat abrupt, insomuch that on weathered faces it is often difficult to get good specimens, owing to the tendency of the vitreous portion to fly off when struck with the hammer. The glass doubtless represents the original condition of the rock of the dyke. It was suddenly chilled and solidified by contact with the walls of the fissure. Inside this external glassy coating, the molten material had time to assume a more or less completely crystalline condition before solidification. Not infrequently the glass shows spherulitic forms, visible to the naked eye, and likewise a more or less distinctly developed perlitic structure. These features, however, are best studied in thin sections of the rock with the aid of the microscope, as will be subsequently referred to.

In some dykes, the glass is not confined to the edges, but runs in strings or broader bands along the central portions. I have found several examples of this peculiarity. The most remarkable of them occurs in the well-known dyke of Eskdale, which runs for so many miles across the southern uplands of Scotland.* This dyke throughout most of its course is a crystalline rock of the less basic type. At Wat Carrick, in Eskdale, it presents an arrangement into three parallel bands. On either side lies a zone about eight feet broad of the usual crystalline material. Between these two marginal portions there is an intercalated mass sixteen to eighteen feet broad, of a very compact and more or less vitreous rock. The demarcation between this central band and the more crystalline zones of the outside is quite sharp, and the two kinds of rock show a totally distinct system of jointing. There can, therefore, be little doubt that the glassy centre belongs to a later uprise than the outer portions, though possibly it may still have been included in the long process of solidification of one originally injected mass of molten material.

Mr C. T. Clough, while mapping for the Geological Survey the extraordinarily numerous dykes in the eastern part of Argyleshire between the Firth of Clyde and Upper Loch Fyne, has observed six or seven examples of dykes showing glassy bands in their centres, with characters similar to those of the Eskdale dyke. He informs me, that he has found an absence of definite and regular joints in the central glassy band, and on the other hand, an irregular set of divisional planes by which the rock is traversed, and which he compares to those seen in true perlitic structure.

* See *Proc. Roy. Phys. Soc. Edin.*, v. (1880) p. 241.

While, as a general rule, the external portions of a dyke are closer-grained than the centre, rare cases occur where the middle is the most finely crystalline part. I am disposed to regard these cases and the glassy centres as forming in reality no true exceptions to the rule, that the outer portions of a dyke consolidated first, and are therefore finest in texture. For the most part, each dyke appears to be due to a single uprise of molten matter, though considerable movements may have taken place within its mass before the whole stiffened into stone. But where, after more or less complete consolidation had taken place, the fissure opened again, or from any other cause the dyke was split along its centre, any lava which rose up the rent would tend to take a finer grain than the material of the rest of the dyke, and might even solidify as glass.

Large scattered crystals of felspar, of an earlier consolidation than that of the minuter forms of the same mineral in the general ground-mass of the rock, give a porphyritic structure and andesitic character to many dykes. Occasionally such crystals attain a considerable size. Mr Clough has observed them in some of the Argyleshire dykes reaching a length of between three and four inches, with a thickness of two inches. Sometimes they are distributed with tolerable uniformity through the substance of the dyke. But not infrequently they may be observed in more or less definite bands parallel with the boundary walls. Unlike the younger lath-shaped and much smaller felspars of the ground-mass, they show no diminution either in size or abundance towards the edge of the dyke. On the contrary, they are often conspicuous in the close-grained marginal strip, and they may be found even in the glassy selvage, and touching the very wall of the fissure. Indeed, they are sometimes more abundant in the outer than in the inner portions of a dyke.

Mr Clough has given me the details of an interesting case of this kind observed by him in Glen Tarsan, Eastern Argyleshire:—"For an inch or so from the edge of this dyke," he remarks, "porphyritic felspars giving squarish sections, and ranging up to one-third of an inch in length, are so abundant as nearly to equal in bulk the surrounding ground-mass. For the next inch and a half, they are decidedly fewer, occupying perhaps hardly an eighth of the area exposed. Then for a breadth of three inches they come in again nearly as abundantly as at the sides; after which they diminish through a band 27 inches broad, where they may form from $\frac{1}{8}$ to $\frac{1}{12}$ of the rock." He found another case where, in a dyke several yards wide, porphyritic felspars, sometimes an inch long, are common along the eastern margin of the dyke in a band about two inches broad, but are nearly absent from the rest of the rock. Elsewhere the crystals are grouped rather in patches than in bands.

Not only are these porphyritic felspars apt to occur in bands parallel with the outer margins of the dykes, but they tend to range themselves with their longer axis in the same direction, thus even on a large scale, visible at some distance, showing the flow-structure, which is so often erroneously regarded as essentially a microscopic arrangement.

Another macroscopic character of the material composing the dykes is the frequent presence of amygdules. It has sometimes been supposed that the amygdaloidal structure may be relied upon as a test to distinguish a mass of molten rock which has reached the surface, from one which has consolidated under considerable pressure below ground. That this supposition, however, is erroneous, is demonstrated by hundreds of dykes in the great system which I am now describing. But the amygdules of a dyke offer certain peculiarities which serve in a general way to mark them off from those of an outflowing lava. They are usually smaller, and more uniform in size, than in the latter rock. They are also more regularly spherical and less frequently elongated in the direction of flow. Moreover, they are not usually distributed through the whole breadth of a dyke, but tend to arrange themselves in lines especially towards its centre (fig. 2). In these central bands the cavities are largest and depart farthest from the regular spherical form, so that for short spaces they may equal in bulk the mass of enclosing rock. In some rare instances, a whole dyke is composed of cellular basalt, like one of the sheets in the plateaux, as may be seen on the north flank of Beinn Suardal, Skye.

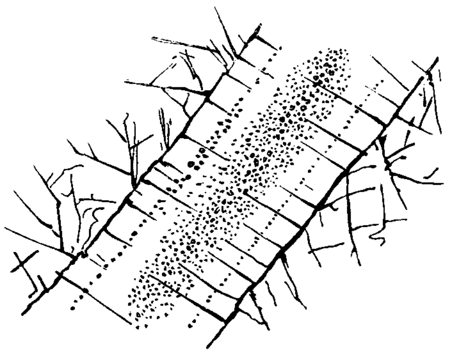


FIG. 2.—Arrangement of lines of Amygdules in a Dyke, Strathmore, Skye.

Besides the common arrangement of fine-grained edges and a more coarsely crystalline centre, instances are found where one of the contrasted portions of a dyke traverses the other in the form of veins. Of these, I think, there are two distinct kinds, probably originating in entirely different conditions. In the first place, they may be of coarser grain than the rest of the rock; but such a structure appears to be of extremely rare occurrence. I have noticed some examples on the coast of Renfrewshire, where strings of a more coarsely crystalline texture traverse the finer-grained body of the rock. Veins of this kind are probably of the same nature as the segregation-veins, to be afterwards referred to as a frequent occurrence among the thicker intrusive sheets. They consist of the same minerals as the rest of the rock, but in a different and more developed crystalline arrangement, and they contain no glassy or devitrified material, except such portions of that of the surrounding ground-mass as may have been caught between their crystalline constituents.

The second kind of veins, which though not common, is of much more frequent occurrence than the first, is more particularly to be met with among the broader dykes, and is distinguished by a remarkable fineness of grain, sometimes approaching the texture of felsite or jasper, and occasionally taking the form of actual glass. Such veins vary from half an inch or less, up to four or five inches in breadth. They run sometimes parallel with the walls of the dyke, but often irregularly in all directions, and for the most part avoid the marginal portions, though now and then coming up to the edge. They never extend beyond the body of the dyke itself into the surrounding rock. Though they have obviously been injected after the solidification of the rock which they traverse, they may quite possibly be extrusions of a deeper unconsolidated portion of the same rock into rents of the already stiffened overlying parts. The field-geologist cannot fail to be struck with the much greater hardness of these fine-grained veins and strings that ramify through the coarsely crystalline dolerite, andesite, or other variety of the broader dykes. He can readily perceive in many cases their more siliceous composition, and the inferences he deduces from the rough observations he can make in the field are confirmed by the results of chemical analysis (see p. 44).

In connection with veins of finer material, that may belong to a late stage of the consolidation of the general body of a dyke, reference may be made here to the occasional occurrence of patches of an exceedingly compact or homogeneous texture immersed in the usual finely crystalline marginal material. They look like angular and subangular portions of the more rapidly cooled outer edge, which have been broken off and carried upward by the still moving mass in the fissure.*

In general, each dyke is composed of one kind of rock, and retains its chemical and mineralogical characters with singular persistence. The difference of texture between the fine-grained chilled margin, with its occasional glassy coating, and the more coarsely crystalline centre is obviously due to the effects of different rates of cooling in what was no doubt originally one uniform molten mass. The glassy central bands, too, though they seem to indicate a rupture of the dyke up the middle, may at the same time quite conceivably be, as I have said, extrusions from a lower portion of the dyke before the final solidification of the whole. The ramifying veins of finer grain that now and then traverse one of the large dykes are likewise explicable as parts of the same stage towards entire consolidation. All these vitreous portions, whether still remaining as glass or having undergone devitrification, are more acid than the surrounding crystalline parts of the rock. They represent the siliceous "mother-liquor," so to speak, which was left after the separation from it of the crystallised minerals, and which, perhaps entangled here and there in vesicles of the slowly cooling and consolidating rock, was ready to be forced up into cracks of the overlying mass during any renewal of terrestrial disturbance.

But examples occur where a dyke, instead of consisting of one rock, is made up of two or more bands of rock which, even if they resemble each other closely, can be shown to be the results of separate eruptions. These, which are obviously not exceptions to the general rule of the homogeneity of dykes, I will consider in a later section of this paper.

Among the petrographical varieties observable in the field is the occasional envelopment of portions of the surrounding rocks in the body of a dyke. Angular fragments torn off from the fissure-walls have been carried upwards in the ascending lava, and now appear more or less metamorphosed, the amount of alteration seeming to depend chiefly upon the susceptibility of the enclosed rock to change from the effects of heat. Cases of such entanglement of foreign substances, however, are of less common occurrence than might have been expected. Occasionally, where the enclosed fragments are oblong,

* See J. J. H. Teall, *Quart. Jour. Geol. Soc.*, xl. (1884) p. 214.

they are arranged with their longer axes parallel to the walls of the dyke, showing flow-structure on a large scale. Mr CLOUGH has lately found some dykes near Dunoon which enclose fragments of schist nearly three feet in length.

One of the most interesting of the macroscropic features of the dykes, is the joints by which they are traversed. These divisional planes are no doubt to be regarded as consequences of the contraction of the original molten rock during cooling and consolidation between its fissure-walls. They are of considerable interest and importance, inasmuch as they furnish a ready means of tracing a dyke when it runs through rock of the same nature as itself, and also help to throw some light on the stages in the consolidation of the material of the dyke.

Two distinct systems of joints are recognisable (fig. 3). Though sometimes combined in the same dyke, they are most conspicuously displayed when each occurs, as it generally does, by itself. The first and less frequent system of joints (*a*) has been determined by lines of retreat, which are parallel to the walls of the dyke. The joints are then closest together at the margin, and may be few or altogether absent in the centre. They are sometimes so numerous, parallel and defined towards the borders of the dyke, as to split the rock up into thin flags. Where transverse joints are also present, these flags are divided into irregular *tesseræ*.

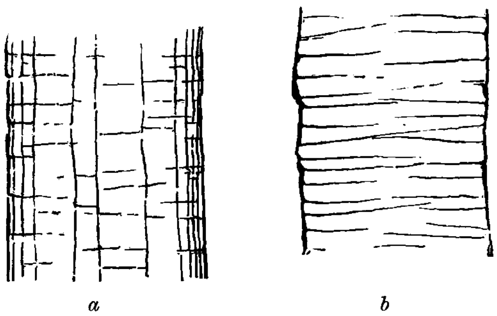
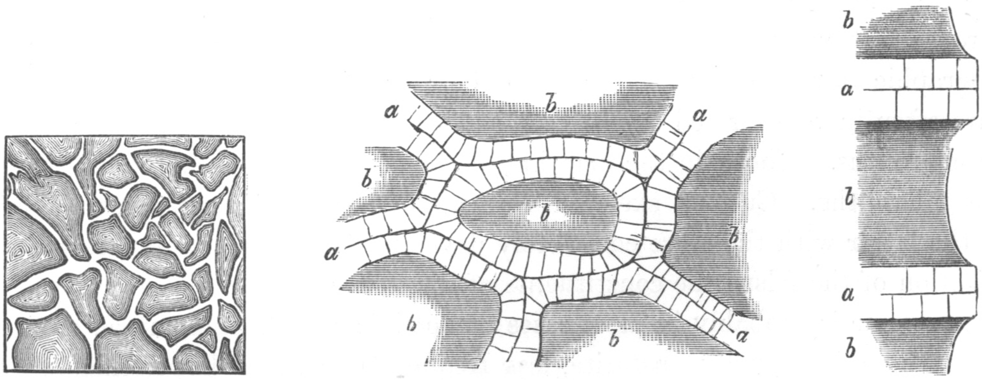


FIG. 3.—Systems of Joints in the Basic Dykes. *a*, parallel ; *b*, transverse.

In the second or transverse system of joints (*b*), which is the more usual, the divisional lines pass across the breadth of the dyke, either completely from side to side or from one wall for a longer or shorter distance towards the other. Where this series of joints is most completely developed the dyke appears to be built up of prisms piled horizontally, or nearly so, one above another. These prisms, in rare instances, are as regular as the columns of a basalt-sheet. Usually, however, they have irregularly defined faces, and merge into each other. Where the prismatic structure is not displayed, the joints starting sharply at the wall of the dyke strike inwards in irregular curving lines. It is such transverse joints that enable the eye, even from a distance, to distinguish readily the course of a dyke up the face of a cliff of basalt-beds, for they belong to the dyke itself, are often at right angles to those of the adjacent basalt, and by their alternate projecting and re-entering angles are banded across with parallel bars of light and shade. Where they traverse not only the general mass of a dyke, but also the "contemporaneous veins" which cross it, it may be plausibly inferred that these veins were injected before the final solidification and contraction of the whole dyke.

One of the most remarkable exhibitions of joint-structure hitherto noticed among these dykes, is that which occurs in the central vitreous band of the Eskdale dyke already referred to. The rock is divided into nearly horizontal prisms, each of which consists of a central more vitreous core and an outer more lithoid sheath. By the coherence of their polygonal and irregular faces, and the greater durability of their material, these sheaths project on the weathered wall of the vitreous centre of the dyke in a curiously reticulated grouping of prominent ribs each about two inches broad (fig. 4), while the vitreous cores, being more readily acted on by the weather, are hollowed out into little cup-shaped depressions. Each rib is thus composed of the sheaths or outer lithoid portions of two prisms, the line of separation being marked by a suture along the centre (fig. 4, B). Between this median suture and the inner glassy core the rib is further cut into small segments by a set of close joints, which are placed generally at right angles to the course of the rib (fig. 4, C). Examined with a lens, the lithoid substance of these sheaths has a dull finely granular aspect, like that of felsitic rocks, with scattered felspars. It is obviously a more devitrified condition of the material which forms the core of each prism. This material presents on a fresh fracture a deep iron-black colour, dull resinous



A. B. C.

FIG. 4.—Joint-Structures in the central vitreous portion of the Eskdale Dyke (B. N. Peach).

A. View of a square yard of the outer wall of the vitreous central band, showing the polygonal arrangement of the prisms and their investing sheath of ribs.

B. View of a smaller portion of the same wall to show the detailed structure of the ribs (*a*, *a*) and their vitreous cores (*b*, *b*).

C. Profile of a part of the weathered face of the wall, showing the way in which the hard ribs or sheaths project at the surface.

lustre, and vitreous texture. It at once recalls the aspect of many pitchstones, and in the early days of petrography was naturally mistaken for that rock. Through its substance numerous kernels of more glassy lustre are dispersed, each of which usually contains one or more amygdules of dull white chalcedony, but sometimes only an empty black cavity. These black glistening kernels of glass, of all sizes up to that of a small bean, scattered through the dull resinous matrix, form with the white amygdules the most prominent feature in the cores; but crystals of felspars may also be observed. Some details of the microscopic characters of this remarkable structure will be given in a subsequent page. The relation of the cores and sheaths to the prismatic jointing of the rock seems to show that devitrification had not been completed when these joints were established, and that it proceeded from the faces of each prism inwards.

2. *Internal Characters.*—Much information has in recent years been obtained regarding the microscopic structure of some of the basic dykes. The crystalline characters of those

in the north of England have been studied by Mr TEALL,* and some of those from the west of Scotland have been investigated by Professor JUDD and Mr COLE.† Taken as a whole, the rocks composing the dykes are found, when examined microscopically, to consist essentially of mixtures of a plagioclase felspar, pyroxene, an iron oxide, and sometimes olivine, usually with more or less interstitial matter.

The felspar appears to be in some cases labradorite, in others anorthite, but there may be a mingling of several species in many of the dykes, as in the augite-andesite of the Santorin eruption in 1866, wherein FOUQUÉ found the larger porphyritic felspars were mainly labradorite, but included also anorthite, while those of the ground-mass were microliths of albite and oligoclase.‡ The large felspars scattered porphyritically through the ground-mass are evidently the result of an early consolidation. They are often cracked, and penetrated by the ground-mass, or even broken into fragments. They also include portions of the ground-mass, and present the zonal growth structure in great perfection. The small felspars of the ground-mass, on the other hand, are as obviously the result of a later crystallisation, for they vary in size and crystallographic development according to their position in the dyke. Those from the centre are often in well-formed crystals, which sometimes pass round their borders into acicular microliths. Those in the marginal parts of the dyke occur chiefly in the form of these microliths. Curious skeleton forms, composed of aggregates of microliths, connect the latter with the more completely developed crystals, and illustrate the mode of crystallisation of the felspathic constituents of the dykes.§

The pyroxene is probably in most cases monoclinic (black or common augite), but is sometimes rhombic (usually enstatite, less frequently perhaps hypersthene). It occurs in (*a*) well-developed crystals, (*b*) crystalline masses with some of the faces of the crystals developed, (*c*) granular aggregates which polarise in one plane, (*d*) separate granules and microscopic microliths, which may be spherical (globulites) or oblong (longulites).

The black iron oxide is sometimes magnetite, sometimes ilmenite, or other titaniferous ore. Apatite not infrequently occurs among the original constituents. Olivine is entirely absent from many of the dykes, and no serpentinous matter remains to indicate that it was ever present in them. But it is also to be met with in numerous cases, either in sparsely scattered or in tolerably abundant crystals. Biotite occasionally appears. Among the secondary products, calcite and pyrites are doubtless the most common. To these must be added quartz, chalcedony, and various zeolitic substances, besides the "viridite" and "opacite," which result from the decomposition of the ferro-magnesian constituents and the oxidation of the ferrous oxides.

In many dykes there is little or no interstitial matter between the crystalline constituents of the ground-mass. In others this matter amounts to a half or more of the whole composition, and from such cases we may trace a series of gradations until

* *Quart. Jour. Geol. Soc.*, vol. xl. (1884).

† *Op. cit.*, vol. xxxix. (1883) p. 444 (basalt-glass); xlii. (1886) p. 49, where Professor JUDD discusses the gabbros, dolerites, and basalts as a whole. See *postea*, p. 77, *note*.

‡ *Santorin et ses Éruptions*, 1879 p. 203.

§ See Mr TEALL'S excellent description of the Cleveland dyke, in the paper above cited.

we arrive at a complete glass containing only the rudimentary forms of crystals (globulites, longulites, &c.), with scattered porphyritic crystals of an earlier consolidation. The process of the disappearance of this original glass may be admirably studied in many dykes. At the outer wall, the glass remains nearly as it was when contact with the cold walls of the fissure solidified it. From that external vitreous layer the successive devitrification products and crystalline growths may be followed inwards until in the central parts of the dyke little trace of the interstitial matter may be left.

The most instructive example of the process of devitrification which has come under my observation occurs in the Eskdale dyke. The central "cores" already referred to present a true glass, which in thin sections is perfectly transparent and almost colourless, but by streaks and curving lines of darker tint shows beautiful flow-structure. The devitrification of this glass has been accomplished by the development of crystallites and crystals, which increase in number until all the vitreous part of the rock disappears. What appears under a low power to be a structureless or slightly dusty glass can be resolved with a higher objective into an aggregate of minute globules or granules (globulites), which average perhaps $\frac{1}{20,000}$ of an inch in diameter. Some of these bodies are elongated and even dichotomous at the ends. These granules are especially crowded upon clear yellow dart-shaped rods, which in turn are especially prominent upon crystals and crystalline grains of augite which bristle with them, while the immediately surrounding glass has become clear. There can be little doubt that these rudimentary bodies are stages in the arrested development of augite crystals. There occur also opaque grains, rods, and trichites, which no doubt consist in whole of magnetite (or other iron oxide), or are crusted over with that mineral.

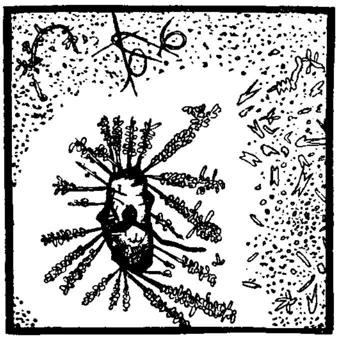


FIG. 5.—Microscopic Structure of the vitreous part of the Eskdale Dyke. This section shows a crystal of augite, *enclosing magnetite* and *surrounded* with microliths, each of which consists of a central pale yellow rod crusted with pale yellow isotropic globulites. The glass around this aggregation is clear, but at a little distance globulites (many of them elongated and dichotomous) abound, with here and there scattered microliths, some of which are curved and spiral. (800 diameters.)*

At least two broad types of microscopic structure may be recognised among the basic dykes. (1) Holocrystalline, or with only a trifling proportion of interstitial matter. This type includes the dolerites and basalts, as well as rocks which German petrographers would class as diabases or diabase-porphyrites. The rocks are very generally characterised by what is known as the ophitic structure, where the lath-shaped felspars penetrate the augite, and are therefore of an earlier consolidation. In such cases there is a general absence of any true interstitial matter. The rocks of this type are often rich in olivine, and appear to be on the whole considerably more basic than those of the second group. It is observable that they increase in numbers from the centre of Scotland westwards, and throughout the region of the basalt-plateaux they form the prevailing

* *Proc. Roy. Phys. Soc. Edin.*, v. (1880) p. 255.

type. (2) In this type there is a marked proportion of interstitial substance, which is inserted in wedge-shaped portions among the crystallised constituents ("intersertal structure" of ROSENBUSCH). The ophitic structure appears to be absent, and olivine is either extremely rare or does not occur at all. The rocks of this group are obviously less basic than those of the other. They form the large dykes that rise so conspicuously through the south of Scotland and north of England, and their general characters are well described by Mr TEALL in the paper already cited. In some instances they enclose abundant porphyritic felspars of earlier consolidation, and then present most of the characters of andesites. Professor ROSENBUSCH has recently extended the name of "Tholeiites" to rocks of this group in the north of England.* The vitreous condition is found in both types, but is perhaps more frequent in the second. The glass of the basalts, however, even in thin slices, is characteristically opaque from its crowded inclusions; while that of the andesitic forms, though black in hand specimens, appears perfectly transparent and sometimes even colourless in thin slices.

3. *Chemical Characters.*—The only one of these to which reference will be made here is the varying proportion of silica. While the dykes as a whole are basic, some of them contain so high a percentage of silica as to link them with the acid rocks. The proportion of this ingredient ranges from less than 50 to nearly 60 per cent. The rocks with the lower percentage of acid are richer in the heavy bases, and have a specific gravity which sometimes rises above 3·0. They include the true dolerites and basalts. Those, on the other hand, with the higher ratio of silica, are poorer in the heavy bases, and have a specific gravity from 2·76 to 2·96. They comprise the "tholeiites," "andesites," and other more coarsely crystalline rocks of the great eastern and south-eastern dykes.†

Not only do the dykes differ considerably from each other in their relative proportions of silica, but even the same dyke may be found to present a similar diversity in different parts of its mass. It has long been a familiar fact that the glassy parts of such basic rocks are more acid than the surrounding crystalline portions. The original magma may be regarded as a natural glass or fused silicate, in which all the elements of the rock were dissolved, and which necessarily became more acid as the various basic minerals crystallised out of it.‡ In the Eskdale dyke the silica percentage of this glassy portion is 58·67, that of the little kernels of black glass dispersed through the rock as much as 65·49.§ In the Dunoon dyke observed by Mr CLOUGH the siliceous or jaspideous veins contain no less than 68·05 per cent. of silica, while the mass of the dyke itself shows on analysis only 47·36 per cent.‖

* *Mikroskopische Physiographie*, 2nd edition, 504 *et seq.*

† For analyses of dykes, see I. L. Bell, *Proc. Roy. Soc.*, xxiii. p. 546; J. S. Grant Wilson, *Proc. Roy. Phys. Soc. Edin.*, v. p. 253; Teall, *Quart. Jour. Geol. Soc.*, xl. p. 209; Judd and Cole, *Quart. Jour. Geol. Soc.*, xxxix. p. 444.

‡ On this subject see a paper by Dr A. Lagorio, "Über die Natur der Glasbasis sowie der Krystallisationsvorgänge im eruptiven Magma," Tschermak's *Mineralog. Mittheil.*, viii. (1887) p. 421.

§ J. S. Grant Wilson, *Proc. Roy. Soc. Phys. Edin.*, v. (1880) p. 253.

‖ Unpublished analyses made by Prof. DITTMAR of Glasgow, and communicated to me by Mr CLOUGH.

4. *Petrographical Nomenclature.*—It is obvious that no one term will suffice to describe a series of rocks presenting such variety of mineralogical and chemical composition as those that form the system of dykes now under discussion. Basalt, dolerite, melaphyre, diabase, augite-porphyrite, diabase-porphyrite, augite-andesite, and doubtless other names might be appropriately applied to different dykes; sometimes, indeed, more than one of these terms might be given to different parts of the same dyke. When the geological history of the dykes, and their connection with the rest of the volcanic phenomena are the subject of inquiry, rather than their petrographical characters, it becomes convenient to adopt some general term which may appropriately describe the whole. The word "basalt" has been so employed, but it is obviously so inapplicable to the more acid and andesitic rocks that its use as a general epithet is objectionable. None of the other specific names are free from the same defect. The old term "trap" would be useful, but it has become obsolete, and its revival might be attended with grave disadvantages. In referring to the dykes of this great system, therefore, I shall speak of them as "the basic dykes," reserving specific names for such individual cases as may require them.

§ 4. Hade.

In the great majority of cases the dykes are nearly or quite vertical. This position is more particularly exhibited by the great single dykes. But occasionally, where one of these crosses a deep valley, a slight hade is perceptible by the deviation of the line of the dyke from its normal course. Sedgwick long ago noticed that the Cleveland dyke has, in places, an inclination of at least 80° to its N.E. side.* In the coal-workings, also, a trifling inclination is sometimes perceptible, especially where a dyke has found its way along a previously existing line of fault, as in several examples in Stirlingshire. But in those districts where the dykes are gregarious, departures from the vertical position are not infrequent, more particularly near the great basalt-plateaux. It was long ago noticed by Necker, that even in such a dyke-filled region as Arran, almost all of the dykes are vertical, though sometimes deviating from that position to the extent of 20°.† Berger found that the angle of deviation among those of the north of Ireland ranges from 9° to 20°, with a mean of 13°.‡ The most oblique examples are probably those which occur in the basalt-plateaux of the Inner Hebrides, where the same dyke in some parts of its course runs horizontally between two beds, across which it also ascends vertically (see fig. 41). But with these minor exceptions, the verticality of the great system of dykes, pointing to the perpendicular fissure-walls between which the molten rock ascended, is one of the most notable features in their geological structure.

§ 5. Breadth.

An obvious characteristic of most dykes is the apparent uniformity of their breadth. Many of them, as exposed along shore-sections, vary as little in dimensions as well-

* *Cambridge Phil. Trans.*, ii. p. 28. † *Trans. Roy. Soc. Edin.*, xiv. p. 677. ‡ *Trans. Geol. Soc.*, iii. p. 227.

built walls of masonry do. Departures from such uniformity may often indeed be noted, whether a dyke is followed laterally or vertically. The largest amount of variation is, of course, to be found among the dykes of the gregarious type, the thinner examples of which may diminish to a width of only one inch or less, while their average breadth is greatly less than in the case of the great solitary dykes. In the district of Strathaird, in Skye, MACCULLOCH estimated the remarkably abundant dykes there developed to vary from 5 to 20 feet in breadth, but with an average breadth of not more than 10 feet.* In the isle of Arran, according to NECKER's careful measurements, most of the dykes range from 2 or 3 to 10 or 15 feet, but some diminish to a few inches, while others reach a width of 20, 30 or even 50 feet.† In the north of Ireland, BERGER observed that the average breadth of thirty-eight dykes traversing primitive rocks (schist, granites, &c.) was 9 feet; and of twenty-four in Secondary rocks, 24 feet.‡

But when we pass to the great solitary dykes, that run so far and so continuously across the country, we encounter much thicker masses of igneous rock. Most of the measurements of these dykes have been made at the surface, and the variations noted in their breadth occur along their horizontal extension. The Cleveland dyke, which is the longest in Britain, varies from 15 to more than 100 feet, with perhaps an average width of between 70 and 90 feet.§ Some of the great dykes that cross Scotland are of larger dimensions. Most of them, however, like that of Cleveland, are liable to considerable variations in breadth when followed along their length. The dyke which runs from the eastern coast across the Cheviot Hills and Teviotdale to the head of the Ale Water, is in some places only 10 feet broad, but at its widest parts is probably about 100 feet. The Eskdale and Moffat dyke is in parts of its course 180 feet wide, but elsewhere it diminishes to not more than 40 feet. These variations are repeated at irregular intervals, so that the dyke alternately widens and contracts as we trace its course across the hills. Some of the dykes further to the north and west attain yet more gigantic proportions. That which crosses Cantyre opposite Ardlamont Point has been measured by Mr J. B. HILL of the Geological Survey, who finds it to be from 150 to 180 feet broad on the shore of Loch Fyne, and to swell out beyond the west side of Loch Tarbert to a breadth of 240 to 270 feet. A dyke near Strathmiglo, in Fife, is about 400 feet wide. The broadest dyke known to me is one which I traced near Beith, in Ayrshire, traversing the Carboniferous Limestone. Its maximum width is 640 feet.

Unfortunately, it is much less easy to get evidence of the width of dykes at different levels in their vertical extension. Yet this is obviously an important point in the theoretical discussion of their origin. Two means are available of obtaining information on the subject—(*a*) from mining operations, and (*b*) from observations at precipices and between hill-crests and valley-bottoms.

* *Trans. Geol. Soc.*, iii. p. 80.

† *Trans. Roy. Soc. Edin.*, xiv. p. 690 *et seq.*

‡ *Trans. Geol. Soc.*, iii. p. 226. He believed that dykes in Secondary rocks reach a much greater thickness than in other formations. My own observations do not confirm this generalisation.

§ At Cockfield, where it has long been quarried, it varies from 15 to 66 feet; at Armathwaite, in the vale of the Eden, it is about 54 feet (J. J. H. Teall, *Quart. Jour. Geol. Soc.*, xl. p. 211).

(*a*) In the central Scottish coal-field and in that of Ayrshire some large dykes have been cut through at depths of two or three hundred feet beneath the surface. But there does not appear to be any well-ascertained variation between their width so far below ground and at the surface. In not a few cases, indeed, dykes are met with in the lower workings of the coal-pits which do not reach the surface or even the workings in the higher coals. Such upward terminations of dykes will be afterwards considered, and it will be shown that towards its upper limit a dyke may rapidly diminish in width.

(*b*) More definite information, and often from a wider vertical range, is to be gathered on coast-cliffs and in hilly districts, where the same dyke can be followed through a vertical range of several hundred feet. But so far as my own observations go, no general rule can be established that dykes sensibly vary in width as they are traced upward. Every one who has visited the basalt precipices of Antrim or the Inner Hebrides, where dykes are so numerous, will remember how uniform is their breadth as they run like ribbons up the faces of the escarpments.* Now and then one of them may be observed to die out, but in such cases (which are far from common among true dykes) the normal width is usually maintained up to within a few feet of the termination.

All over the southern half of Scotland, where the dykes run along the crests of the hills and also cross the valleys, a difference of level amounting to several hundred feet may often be obtained between adjacent parts of the same dyke. But the breadth of igneous rock is not perceptibly greater in the valleys than on the ridges. The depth of boulder clay and other superficial deposits on the valley bottoms, however, too frequently conceals the dykes at their lowest levels. Perhaps the best sections in the country for the study of this interesting part of dyke-structure are to be found among the higher hills of the Inner Hebrides, such as the quartzites of Jura and the granophyres and gabbros of Skye. On these bare rocky declivities, numerous dykes may be followed from almost the sea-level up to the rugged and splintered crests, a vertical distance of between 2000 and 3000 feet. The dykes are certainly not as a rule sensibly less in width on the hill tops than in the glens. So far, therefore, as I have been able to gather the evidence, there does not appear to me to be, as a general rule, any appreciable variation in the width of dykes for at least 2000 or 3000 feet of their descent. The fissures which they filled must obviously have had nearly parallel walls for a long way down.

§ 6. Interruptions of Lateral Continuity.

In tracing the great single dykes across the country, the geologist is often surprised to meet with gaps, varying in extent from a few hundred feet to several miles, in which no trace whatever of the igneous rock can be detected at the surface. This disappearance is not always explicable by the depth of the cover of superficial accumulations;

* This point did not escape the attention of that excellent observer, Berger, in his examination of the dykes in the north of Ireland. We find him expressing himself thus :—"The depth to which the dykes descend is unknown; and after having observed the sections of a great many along the coast in cliffs from 50 to 400 feet in height, I have not been able to ascertain (except in one or two cases) that their sides converge or have a wedgeform tendency" (*Trans. Geol. Soc.*, iii. p. 227).

for it may be observed over ground where the naked rocks come almost everywhere to the surface, and where, therefore, if the conspicuous material of the dykes existed, it could not fail to be found. No dyke supplies better illustrations of this discontinuity than that of Cleveland. Traced north-westward across the Carboniferous tracts that lie between the mouth of the Tees and the Vale of the Eden, this dyke disappears sometimes for a distance of six or eight miles. In the mining ground round the head of the South Tyne the rocks are bare, so that the absence of the dyke among them can only be accounted for by its not reaching the surface. Yet there can be no doubt that the various separated exposures, which have the same distinctive lithological characters and occur on the same persistent line, are all portions of one dyke which is continuous at some depth below ground. We have thus an indication of the exceedingly irregular upward limit of the dykes, as will be more particularly discussed further on.

But there are also instances where the continuity is interrupted and then resumed on a different line. One of the best illustrations of this character is supplied by the large dyke which rises through the hills about a mile south of Linlithgow and runs westward across the coal-field. At Blackbraes it ends off in a point, and is not found again to the westward in any of the coal-workings. But little more than quarter of a mile to the south a precisely similar dyke begins, and strikes westward parallel to the line of the first one. The two separated strips of igneous rock overlap each other for about three-quarters of a mile. But that they are merely interrupted portions of what is really a single dyke can hardly be questioned. A second example is furnished by another of the great dykes of the same district, which after running for about 12 miles in a nearly east and west direction suddenly stops at Chryston, and begins again in the same direction, but on a line about a third of a mile further north. Such examples serve to mark out irregularities in the great fissures up which the materials of the dykes rose.

§ 7. Length.

In those districts where the small and crowded dykes of the gregarious type are developed, one cannot usually trace them for more than a short distance. The longest examples known to me are those which have recently been mapped with much patience and skill by Mr Clough in Eastern Argyleshire. Some of them he has been able to track over hill and valley for four or five miles, though the great majority are much shorter. In Arran and in the Inner Hebrides, it is seldom possible to follow what we can be sure is the same dyke for more than a few hundred yards. This difficulty arises partly, no doubt, from the frequent spread of peat or other superficial accumulation which conceals the rocks, and partly also from the great number of dykes and the want of sufficiently distinct lithological characters for the identification of any particular one. But making every allowance for these obstacles, we are compelled, I think, to regard the gregarious dykes as essentially short as well as relatively irregular.

In striking contrast to these, come the great solitary dykes. In estimating their length, as I have already remarked, we must bear in mind the fact that they occasionally undergo interruptions of continuity owing to the local failure of the igneous material to rise to the level of what is now the surface of the ground. A narrow wall-like mass of augite-andesite, dolerite, or basalt which sinks beneath the surface for a few hundred yards, or for several miles, and reappears on the same line with the same petrographical characters, while there may be no similar rock for miles to right and left, can only be one dyke prolonged underneath in the same great line of fissure. But even if we restrict our measurements of length to those dykes or parts of dykes where no serious interruption of continuity takes place, we cannot fail to be astonished at the persistence of these strips of igneous rock through the most diverse kinds of geological structure. A few illustrative examples of this feature may be selected. It will be observed that the longest and broadest dykes are found furthest from the basalt-plateaux, while the shortest and narrowest are most abundant near these plateaux.

Not far from what I have taken provisionally as the northern boundary of the dyke region, two dykes occur which have been mapped from the head of Loch Goil by Arrochar across Lochs Lomond and Katrine by Ben Ledi to Glen Artney, whence they strike into the Old Red Sandstone of Strathmore, and run on to the Tay near Perth—a total distance of about 60 miles. If the dyke which continues in the same line on the other side of the estuary of the Tay beyond Newburgh, is a prolongation of one of these, then its entire length exceeds 70 miles. A few miles further south, one of a group of dykes can be followed from the heart of Dumbartonshire by Callander across the Braes of Doune to Auchterarder—a distance of 47 miles, with an average breadth of more than 100 feet. In the district between the Forth and Clyde a number of long parallel dykes can be traced for many miles across hill and plain, and through the coal-fields. One of these is continuous for 25 miles from the heart of Linlithgowshire into Lanarkshire. Still longer is the dyke which runs from the Firth of Forth at Grangemouth westward to the Clyde, opposite Greenock—a distance of about 36 miles. Coming southward, we encounter a striking series of single dykes on the uplands between the counties of Lanark and Ayr, whence they strike into the Silurian hills of the southern counties. One of these runs across the crest of the Haughshaw Hills, and can be followed for some 30 miles. But if, as is probable, it is prolonged in one of the dykes that traverse the moorlands of the north of Ayrshire and south of Renfrewshire to the Clyde, its actual length must be at least twice that distance. The great Moffat and Eskdale dyke strikes for more than 50 miles across the south of Scotland and north of England. The Hawick and Cheviot dyke runs for 26 miles in Scotland and for 32 miles in Northumberland. But the most remarkable instance of persistence is furnished by the Cleveland dyke. From where it is first seen near the coast-cliffs of Yorkshire it can be followed, with frequent interruptions, during which for sometimes several miles no trace of it appears at the surface, across the north of England and as far as Dalston Hall south of Carlisle, beyond which the ground onwards to the Solway Firth is deeply covered with superficial deposits. The total distance through which this dyke can be recognised is about 110 miles. But it probably goes much further still. On the opposite side of the Solway, a dyke which runs in the same line, rises through the Permian strata a little to the east of the mouth of the Nith. Some miles further to the north-west, near Moniaive, Mr J. HORNE, in the progress of the Geological Survey, traced a dark compact dyke with kernels of basalt-glass near its margin, running in the same north-westerly direction. Still further on in the same line, another similar rock is found high on the flanks of the lofty hill known as Windy Standard. And lastly, in the Ayrshire coal-field, a dyke still continuing the same trend, runs for several miles, and strikes out to sea near Prestwick. It cannot, of course, be proved that these detached Scottish protrusions belong to one great dyke, or that if such a continuous dyke exists, it is a prolongation of that from Cleveland. At the same time, I am on the whole inclined to connect the various outcrops together as those of one prolonged subterranean wall of igneous rock. The distance from the last visible portion of the Cleveland dyke near Carlisle to the dyke that runs out into the Firth of Clyde near Prestwick, is about 80 miles. If we consider this extension as a part of the great north of England dyke, then the total length of this remarkable geological feature will be about 190 miles.

§ 8. PERSISTENCE OF MINERAL CHARACTERS.

Not less remarkable than their length is the preservation of their normal petrographical characters by some dykes for long distances. In this respect the Cleveland dyke may again be cited as a typical example. The macroscopic and microscopic structures of the rock of this dyke distinguish it among the other eruptive rocks of the north of England. And these peculiarities it maintains throughout its course.* Similar though less prominent uniformity may be traced among the long solitary dykes of the south of Scotland, the chief variations in these arising from the greater or less extent to which the original glassy magma has been retained. The same dyke will at one part of its course show abundant glassy matter even to the naked eye, while at a short distance the vitreous ground-mass has been devitrified, and its former presence can only be detected with the aid of the microscope.

§ 9. DIRECTION.

Another characteristic feature of the dykes is their generally rectilinear course. So true are they to their normal trend that, in spite of varying inequalities of surface and wide diversities of geological structure in the districts which they traverse, they run over hill and dale almost with the straightness of lines of Roman road. In the districts where they assume the gregarious type, and depart most widely from the character of the great solitary dykes, they still tend to run in straight or approximately straight lines, or, if wavy in their course, to preserve a general parallelism of direction.

Yet even among the great persistent dykes instances may be cited where the rectilinear trend is exchanged for a succession of zig-zags, though the normal direction is

* See the careful examination of this dyke by Mr Teall, *Quart. Jour. Geol. Soc.*, xl. p. 209.

on the whole maintained. In such cases, it is evident that the fissures were not long straight dislocations like the larger lines of fault in the earth's crust, but were rather notched rents or cracks which, though keeping on the whole one dominant direction, were continually being deflected for short distances to either side. As a good illustration of this character, reference may be made to the Cheviot and Hawick dyke. In Teviotdale this dyke can be followed continuously among the rocky knolls, so that its deviations can be seen and mapped. From the median line of average trend the salient angles sometimes retire fully a quarter of a mile on either side. Some examples of the same feature may be noticed in the Eskdale dyke. The large dyke which runs westward from Dunoon has been observed by Mr CLOUGH to change sharply in direction three times in four miles, running sometimes for a short distance at a right angle to its general direction (see fig. 17).

Among these solitary dykes also, though the persistence of their trend is so predominant, there occur instances where the general direction undergoes great change. Some of the most remarkable cases of this kind have been mapped by Mr B. N. PEACH and Mr R. L. JACK, in the course of the Geological Survey of Perthshire. Several important dykes strike across the Old Red Sandstone plain for many miles in a direction slightly south of west. But when they approach the rocks of the Highland border in Glen Artney, they bend round to south-west, and continue their course along that new line.

In my early paper on the "Chronology of the Trap-Rocks of Scotland,"* I called attention to the dominant trend of the dykes from N.W. to S.E. Subsequent research has shown this to be on the whole the prevalent direction throughout the whole region of dykes. But the detailed mapping, carried on by my colleagues and myself in the Geological Survey, has brought to light some curious and interesting variations from the normal trend. In the districts where dykes of the gregarious type abound there is sometimes no one prevalent direction, but the dykes strike to almost all points of the compass. Of the Arran dykes, so carefully catalogued by NECKER, only about a third have a general north-westerly course. But in Eastern Argyleshire the abundant dykes mapped by Mr CLOUGH trend almost without exception towards N.N.W. In the north of Ireland BERGER found the direction of thirty-one dykes to vary from 17° to 71° W. of N., giving a mean of N. 36° W.† In Islay, Jura, Eigg, Mull, and Skye the mean of several hundred observations has given me similar results.

It appears therefore that though there is sometimes extraordinary local diversity in the direction of the dykes in those districts where they present the gregarious type, the general north-westerly trend can usually still be recognised. But when we turn to the long massive solitary dykes, we soon perceive a remarkable change in their direction as we follow them northward into Scotland. In the paper just referred to, I pointed out how the general north-westerly trend becomes east and west in the Lothians, with a tendency to veer a little to the south of west and north of east. This departure from the normal direction is now seen to be part of a remarkable radial arrangement of the dykes.

* *Trans. Roy. Soc. Edin.*, xx. p. 650.

† *Trans. Geol. Soc.*, iii. p. 225.

Beginning at the southern margin of the dyke-region, we have the notable example of the Cleveland dyke, which in its course from Cleveland to Carlisle runs nearly W. 15° N. The Eskdale dyke has an average trend of W. 32° N., and the same general direction is maintained by the group of dykes which run from the Southern Uplands across the south-west of Lanarkshire and north-east of Ayrshire. But as we proceed northwards we observe the trend to turn gradually round towards the west. The dyke that runs from near the mouth of the Coquet across the Cheviot Hills to beyond Hawick has a general course of W. 8° N. In the great central coal-field of Scotland the average direction may be taken to be nearly E. and W., the same dyke running sometimes to the north, and sometimes to the south of that line. But immediately to the north a decided tendency to veer round southwards makes its appearance. Thus the long dyke which runs from the Carse of Stirling through the Campsie Fells to the Clyde west of Leven, has a mean direction of W. 5° S. This continues to be the prevalent trend of the remarkable series of dykes which crosses the Old Red Sandstone plains, though some of these revert in whole or in part to the more usual direction by keeping a little to the north of west. Even as far as Loch Tay and the head of Strathardle, the course of the dykes continues to be to the south of west. Tracing these lines upon a map of the country we perceive that they radiate from an area lying along the eastern part of Argyleshire and the head of the Firth of Clyde (see Plate I.).

§ 10. Termination Upwards.

It was pointed out many years ago by Winch that some of the dykes which traverse the Northumberland coal-field do not cut the overlying Magnesian Limestone. The Hett dyke, south of Durham, which no doubt belongs to the ancient series of igneous protrusions already referred to, is said to end off abruptly against the floor of the limestone.* Here and there, among the precipices of the Inner Hebrides, a dyke may be seen to die out before it reaches the top of the cliff. But in the vast majority of

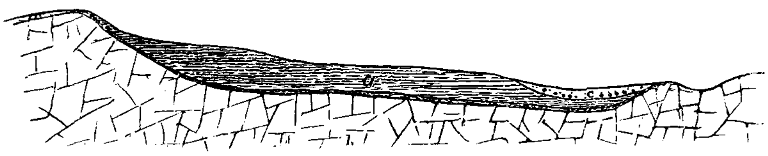


Fig. 6.—Section along the line of the Cleveland Dyke at Cliff Ridge, Guisbrough (G. Barrow), scale, 12 inches to 1 mile.

cases, no evidence remains as to how the dykes terminated upwards. I have referred to the occasional interruptions of the continuity of a dyke, where, though the rock does not reach the surface, it must be present in the fissure underneath. Such interruptions show that, in some places at least, there was no rise of the rock even up to the level of what is now the surface of the ground, and that the upward limit of the dykes must have been exceedingly irregular.

* This is expressed in the Geological Survey map, Sheet 93, N.E.

Excellent illustrations of this feature are supplied by sections on the line of the Cleveland dyke. Towards its south-eastern extremity this great band of igneous rock ascends from the low Triassic plain of the Tees into the high uplands of Cleveland. Its course across the ridges and valleys there has been carefully traced for the Geological Survey by Mr G. Barrow, who has shown that over certain parts of its course it does not reach the surface, but remains concealed under the Jurassic rocks, which it never succeeded in penetrating. But that in places it comes within a few feet of the soil is shown by the baked shale at the surface, for the alteration which it has induced on the surrounding rocks only extends a few feet from its margin. These interruptions of continuity show how uneven is the upper limit of the dyke. The characteristic porphyritic rock may be observed running up one side of a hill to the crest, but never reaching the surface on the other side. At Cliff Ridge, for example, about three miles south-west of Guisbrough, Mr Barrow has followed it up to the summit on the west side; but has found that on the east side it does not pierce the shales, which there form the declivity. This structure is represented in fig. 6. The vertical distance between the summit to the left, where the dyke (*b*) disappears, and the point to the right, where the Lias shale (*a*) of the hill-side is concealed by drift (*c*), amounts to 250 feet, the horizontal distance being a little more than 900 feet. But as the shale when last seen at the foot of the slope is quite unaltered, the dyke must there be still some little distance beneath the surface, so that the vertical extension of this upward tongue of the dyke must be more than 250 feet. Mr Barrow, to whom I am indebted for these particulars, has also drawn the accompanying section (fig. 7) along the course of the dyke for a distance of nearly 11 miles eastward from the locality represented in fig. 6. From this section, it will be observed that in that space there are at least three tongues or upward projections of the upper limit of the dyke. Several additional examples of the same structure are to be seen further east towards the last visible outcrop of the dyke.

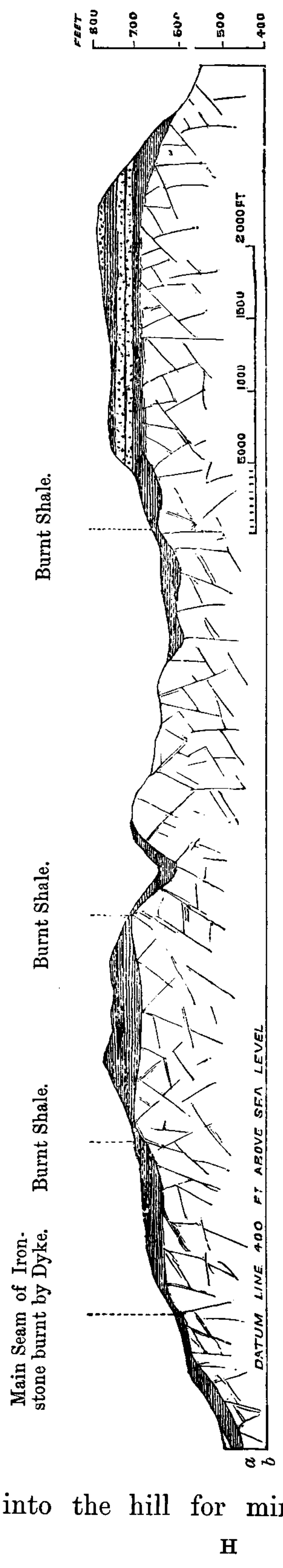


FIG. 7.—Section along the course of the Cleveland Dyke, at the head of Lonsdale, Yorkshire (G. Barrow, in *Memoirs of the Geol. Survey*, Geology of Cleveland, p. 61). *a*. Liassic shales, sandstones, and ironstones; *b*, The Dyke.

Another feature connected with the upward termination of the dyke is well seen in some parts of the ground through which the two foregoing sections are taken. Mr Barrow informs me that at Ayton a level course has been driven into the hill for mining operations, at a height of 400 feet above sea-level, and the dyke has there been ascertained to be 80 feet broad. Higher on the hill, close to the 750 feet contour-line, its breadth is only 20 feet, so that it narrows upward as much as 60 feet in a vertical height of 350 feet. Its contraction in width during the last twenty feet is still more rapid, and in the last few yards it diminishes to two or three feet, and has a rounded top over which the strata are bent upward. The accompanying section (fig. 8) across the upper part of the dyke will make these features clearer.

Further to the west an exposure of the upper limit of the dyke has been described and figured by Mr TEALL. In 1882, at one of the Cockfield quarries (fig. 9), the dyke

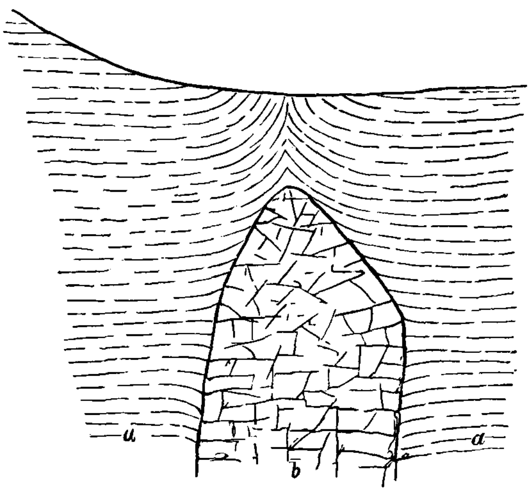


FIG. 8.—Section across the extreme upper limit of the Cleveland Dyke, Ayton, on the scale of 20 feet to one inch (G. Barrow). *a*, Jurassic shales, &c.; *b*, Dyke.

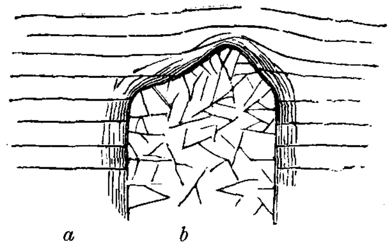


FIG. 9.—Upper limit of the Cleveland Dyke in quarry near Cockfield (after J. J. H. Teall). *a*, *a*, Carboniferous shales; *b*, Dyke.

was "seen to terminate upwards very abruptly in the form of a low and somewhat irregular dome, over which the Coal Measure shales passed without any fracture, and only with a slight upward arching." *

Near the other or north-western termination of this great dyke, similar evidence is found of an uneven upper limit. After an interrupted course through the Alston moors, the dyke reaches the ground that slopes eastward from the edge of the Cross Fell escarpment. Its highest visible outcrop is at a height of 1700 feet. But westwards from that point the dyke disappears under the Carboniferous rocks, and does not emerge along the front of the great escarpment that descends upon the valley of the Eden, where among the naked scarps of rock it would unquestionably be visible if it reached the surface. Its upper edge must rapidly descend somewhere behind the face of the escarpment, for the igneous rock crops out a little to the west of the foot of the cliff, at a height of about 1000 feet below the point where it is last seen on the hills above. Here the top of the dyke has a vertical drop of not less than 1000 feet, in a horizontal distance of five miles, as shown in fig. 10, which has been drawn for me by Mr J. G. GOODCHILD.

* *Quart. Jour. Geol. Soc.*, xl. p. 210.

It will be observed that in these sections (figs. 7 and 10) there is a curiously approximate coincidence between the inequalities in the upper surface of the dyke and those in the form of the overlying ground. The coincidence is too marked and too often repeated to be merely accidental. Whether the ancient topographical features had any influence in determining, by cooling or otherwise, the limit of the upward rise of the lava, or whether the dyke, even though concealed, has affected the progress of the denudation of the ground overlying it, is a question worthy of fuller investigation.

§ 11. Known Vertical Extension.

Closely connected with the determination of the upper limit reached by the dykes, is the total vertical depth to which they can be traced. Of course, the depth of the original reservoir of molten rock which supplied them remains unknown, and probably undiscoverable. But it is possible in many cases to determine at least the inferior limit of the thickness of rock through which the molten material of the dykes has ascended. In the dark gabbro hills of Skye, numerous dykes may be seen climbing from the glens right up the steep rugged acclivities and over the crests. In these and similar cases, we can actually trace the dykes through a vertical thickness of more than 3000 feet of rock. The dykes which cross Loch Lomond and ascend the hills on either side of that deep depression must rise through at least as great a thickness. But where a knowledge of the geological structure of the ground enables us to estimate the bulk of the successive rock-formations which underlie the surface, it can be shown that the lava ascended through a much greater depth of rock. Measurements of this kind can best be made towards the eastern end of the Cleveland dyke, where the different sedimentary groups have not been seriously disturbed, and where from natural sections and artificial borings their thicknesses are capable of satisfactory computation. The highest bed of the Jurassic series anywhere touched by the dyke is the Cornbrash. It is certain, therefore, that the igneous rock rises through all the subjacent members of the Jurassic series up to that horizon. There can be no doubt also that the Trias and Magnesian Limestone continue in their normal thickness underneath the Jurassic strata. To what extent the Coal-Measures exist under Cleveland has not been ascertained; possibly they have been entirely denuded from that area, as from the ground to the west. But the Millstone Grit and Carboniferous Limestone probably extend over the district in full development; and below them there must lie a vast depth of Upper and Lower Silurian strata,

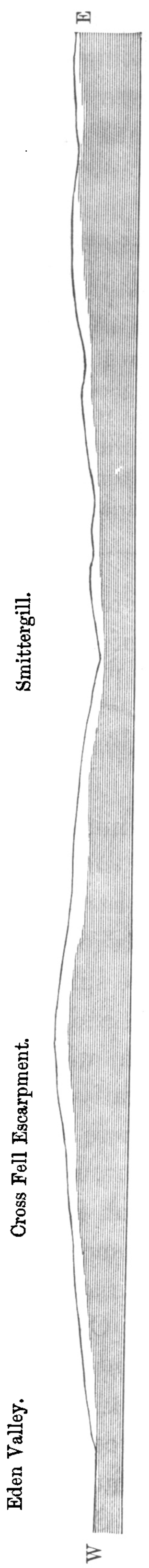


Fig. 10.—Section along the course of the Cleveland Dyke across the Cross Fell escarpment (J. G. Goodchild). The shaded part shows the position of the dyke, the unshaded part overlying it marks where the dyke does not reach the surface (scale of 1 inch to 1 mile).

probably also of still older Palæozoic rocks, and beneath all the thick Archæan platform. Tabulating these successive geological formations, and taking only the ascertained thickness of each in the district, we find that they give the results shown in the subjoined table.*

Strata Cut by the Cleveland Dyke.

	Feet.
Cornbrash—	
Lower Oolite and Upper Lias, as proved by bore-hole on Gerrick Moor,	950
Middle and Lower Lias, ascertained from measurement of cliff-sections and from mining operations to be more than	850
New Red Sandstone and Marl, found by boring close to the Tees to exceed	1,600
Magnesian Limestone, at least	500
Coal-Measures, possibly absent	0
Millstone Grit, not less than	500
Carboniferous Limestone series, at least	3,000
Silurian rocks, probably not less than	10,000
	17,400

There is thus evidence that this dyke has risen through probably more than three miles of stratified rocks. How much deeper still lay the original reservoir of molten material that supplied the dyke we have at present no means of computing.

§ 12. Branches and Veins.

It might have been anticipated that the uprise of such abundant masses of molten rock in so many long and wide fissures would generally be attended with the intrusion of the same material into lateral rents and irregular openings, so that each dyke would have a kind of fringe of offshoots or processes striking from it into the surrounding ground. It might have been expected also that dykes would often branch, and that the arms would come together again and enclose portions of the rocks through which they rise. But in reality such excrescences and bifurcations are of comparatively rare occurrence. As a rule, each dyke is a mere wall of igneous rock, with little more projection or ramification than may be seen in a stone field-fence. Among the short, narrow, and irregular dykes of the gregarious type branchings are occasionally seen, and in some districts are extraordinarily abundant. But among the great single dykes such irregularities are far less common than might have been looked for. A few characteristic examples from each type of dyke may here be given.

The Cleveland dyke, which in many respects is typical of the great solitary dykes of the country, has been traced for many miles without the appearance of a single offshoot of any kind. Yet here and there along its course it departs from its usual regularity. As it crosses the Carboniferous tracts of Durham and Cumberland, there appear near its course lateral masses of eruptive rock, most of which doubtless belong to the much older "Whin Sill." But there is at least one locality, at Bolam near Cockfield, in the county

* Drawn up for me by Mr Barrow.

of Durham, where the dyke, crossing the Millstone Grit, suddenly expands into a boss, and immediately contracts to its usual dimensions. Around this knot several short dykes or veins seem to radiate from it. The dyke has been quarried here, and its relations to the surrounding strata have been laid bare, as will be again referred to a little further on.*

Among the great persistent dykes of Scotland the absence of bifurcation and lateral offshoots offers a striking contrast to the behaviour of the dykes in those districts where they are small in size and many in number. But exceptions to the general rule may be gathered. Thus the Eskdale dyke is flanked at West Carrick with a large lateral vein, which is almost certainly connected with the main fissure. The Hawick and Cheviot dyke splits up on the hill immediately to the east of the town of Hawick, sends off some branches, and then resumes its normal course (fig. 11). Again, one of the two nearly parallel dykes which run from Loch Goil Head across Ben Ledi into Glen Artney bifurcates at the foot of that valley, its northern limb (about two miles long) speedily

Fig. 11.—Branching portion of the great Dyke near Hawick (length about 1 mile).

Fig. 12.—Branching Dyke at foot of Glen Artney (length about 4 miles).

dying out, and its southern branch throwing off another lateral vein, and then continuing eastward as the main dyke (fig. 12).

In the districts of gregarious dykes, however, abundant instances may be found of dykes that branch, and of others that lose the parallelism of their walls, become irregular in breadth, direction, and inclination, so as to pass into those intrusive forms that are more properly classed as veins. Excellent illustrations of bifurcating dykes may be observed along the shores of the Firth of Clyde, particularly on the eastern coast line of the isle of Arran. The venous character has been familiar to geologists from the sketches given by Macculloch from the lower parts of the cliffs of Trotternish in Skye.† But still more striking examples are to be seen in the breaker-beaten cliffs of Ardnamurchan. The pale Secondary limestones and calcareous sandstones of that locality are traversed by a series of dark basic veins, and the contrast of tint between the two kinds of rock is so marked as even to catch the eye of casual tourists in the passing steamboats. The

* This locality was well described by Sedgwick, in his early paper on Trap-Dykes in Yorkshire and Durham, *Trans. Cambridge Phil. Soc.*, ii. p. 27.

† *Western Islands*, plate xvii.

veins vary in width from less than an inch to several feet or yards. They run in all directions and intersect each other, forming such a confused medley as requires some patience on the part of the geologist who would follow out each independent ribbon of injected material in its course up the cliffs, or still more, would sketch their ramifications in his note-book. A good, though perhaps somewhat exaggerated, illustration of their general character was given by MACCULLOCH.* The accompanying figure (fig. 13) is less sensational, but represents with as much accuracy as I could reach, the network of veins near the foot of the cliffs. One conspicuous group of veins, which seen from a distance looks like a rude sketch of a lug-sail traced in black outline upon a pale ground, is known to the boatmen as "M'Niven's Sail."

As a general rule, the narrower the vein the finer in grain is the rock of which it consists. This compact dark homogeneous material has commonly passed by the name

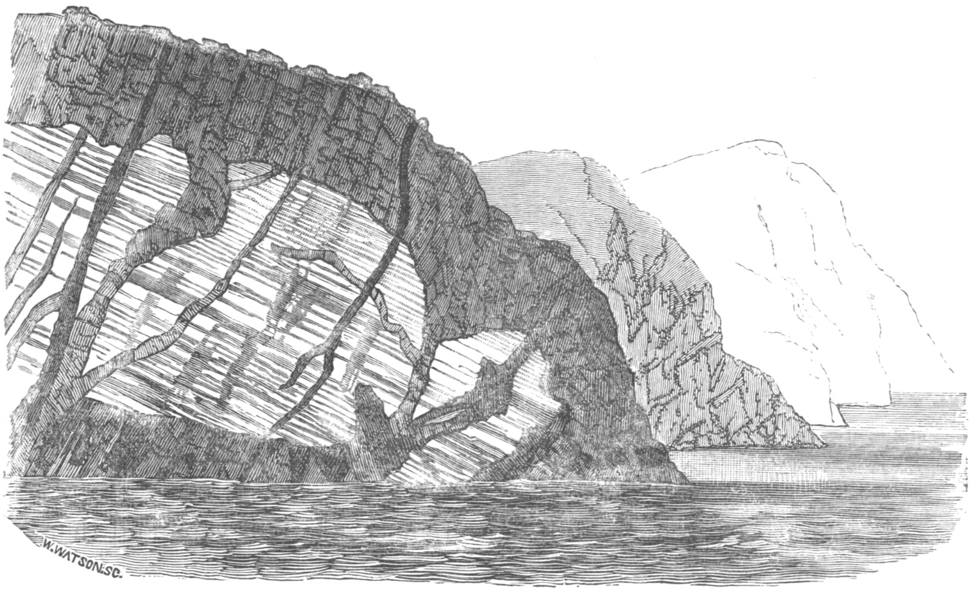


FIG. 13.—Basic Veins traversing Secondary Limestone and Sandstone on the coast cliffs, Ardnamurchan.

of "basalt," but its minuteness of texture probably in most cases arises from local rapidity of cooling, and it may be the same substance which, where in larger mass in the immediate neighbourhood, has solidified as one of the other pyroxene-plagioclase-magnetite rocks.

With regard to the places where such abundant tortuous veins are more especially developed, I may remark that they are particularly prominent under a thick overlying mass of erupted rock, such as a great intrusive sheet, or the bedded basalts of the plateaux, or where there is good reason to believe that such a deep cover, though now removed by denudation, once overspread the area in which they appear. It will be shown in the sequel that such horizons have been peculiarly liable to intrusions of igneous material of various kinds, and at many different intervals, during the volcanic period. A thick cake

* *Op. cit.*, plate xxxiii. fig. 1.

of crystalline rock seems to have offered such resistance to the uprise of molten material through it, that when the subterranean energy was not sufficient to rend it open by great fissures, and thus give rise to dykes, the lavas were forced into such irregular cracks as were made partly in the softer rocks underneath and partly in the cake itself, or found escape along pre-existing divisional planes. In Ardnamurchan, round the Cuillin Hills of Skye, and in Rum, the overlying resisting cover now consists mainly of gabbro sheets. In the east of Skye, in Eigg, and in Antrim, it is made up of the thick mass of the plateau-basalts.

§ 13. Connection of Dykes with Intrusive Sheets.

Every field-geologist is aware how seldom he can actually find the vent or pipe up which rose the igneous rock that now forms those massive beds which he denominates intrusive sheets. He might well be pardoned were he to anticipate that, in a district much traversed by dykes, there should be many examples of intrusive sheets and frequent opportunities of tracing their connection with the fissures from which their material might be supposed to have been supplied. But such an expectation is singularly disappointed by an actual examination of the Tertiary volcanic region of Britain. That there are many intrusive sheets belonging to the great volcanic period with which I am now dealing, I shall endeavour to show in the sequel. But it is quite certain that though these sheets have of course each had its subterannean pipe or fissure of supply, they can only in very rare instances be directly traced to the system of dykes. On the other hand, the districts where great single dykes are most conspicuous, are for the most part free from intrusive sheets, except those of much older date, like the Carboniferous Whin Sill of Durham and the diabases of Linlithgowshire.

Yet a few interesting examples of the relation of dykes to sheets have been noticed. The earliest observed instances were those figured and described by MACCULLOCH in his *Western Islands of Scotland*. Among them one has been familiar to geologists from having done duty in text-books of the science for more than half a century. I allude to the diagram of "Trap and Sandstone near Suishnish."* In that drawing seven dykes are shown as rising vertically through the horizontal sandstone, and merging into a thick overlying mass of "trap." The author in his explanation leaves it an open question "whether the intruding material has ascended from below and overflowed the strata, or has descended from the mass," though from the language he uses in his text we may infer that he was inclined to regard the overlying body as the source of the veins below it.†

The section given by MACCULLOCH, however, does not quite accurately represent the facts. The narrow dykes there drawn have no connection with the overlying sheet, but are part of the abundant series of basaltic dykes found all over Skye. The feeder of the sheet was undoubtedly the thick dyke which descends the steep bank immediately on the

* *Op. cit.*, pl. xiv. fig. 4.

† Vol. i. pp. 384, 385.

southern front of Carn Dearg (636 feet high). The accompanying figure (fig. 14) shows what I believe to be the true geological structure of the locality, but the actual junction of the dyke and sheet is concealed under the talus of the slope. I shall have occasion in a later part of this paper to refer again to this section in connection with the history of intrusive sheets.

SEDGWICK, in the paper already quoted, gave an account and figure of the expansion of the Cleveland dyke at Bolam, to which allusion has already been made. He showed that from a part of the dyke which is unusually contracted a great lateral extension of the igneous rock takes place on either side over beds of shale and coal. While in the dyke the prisms are as usual directed horizontally inward from the two walls, those in the connected sheet are vertical, and descend upon the surface of highly indurated strata on which the sheet rests.

But by far the most important examples known to me are those which occur in the coal-field of Stirlingshire. In that part of the country, the remarkable group of dykes already referred to, lying nearly parallel to each other and from half a mile to about

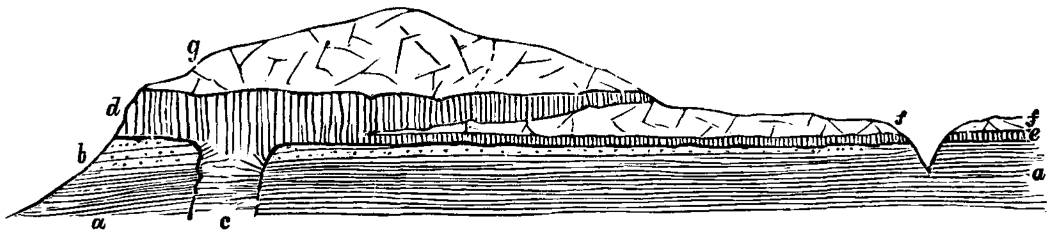


FIG. 14.—Section showing the connection of a Dyke with an Intrusive Sheet, Point of Suisnish, Skye. *g*, Granophyre of Carn Dearg; *f*, similar rock, which appears eastward under the "sill" (*d*); *e*, intrusive sheet of fine-grained "basalt"; *d*, intrusive sheet or "sill" of coarse dolerite, 200 feet thick at its maximum, and rapidly thinning out; *c*, dyke or pipe of finer grain than *d*; *b*, yellowish-brown shaly sandstones, and *a*, dark sandy shales (Lias).

three miles apart, runs in a general east and west direction. From one of these dykes no fewer than four sheets or "sills" strike off into the surrounding Coal-Measures. The largest of them stretches southwards for three miles, but the same rock is probably continued in a succession of detached areas which spread westwards through the coal-field and circle round to near the two western sheets that proceed from the same dyke. Another thick mass of similar rock extends on the north side of the dyke for two and a half miles down the valley of the river Avon. These various processes, attached to or diverging from the dyke, are unquestionably intrusive sheets, which occupy different horizons in the Carboniferous series. The one on the north side has inserted itself a little above the top of the Carboniferous Limestone series. Those on the south side lie on different levels in the Coal-Measures, or rather they pass transgressively from one platform to another in that group of strata.

No essential difference can be detected by the naked eye between the material of the dyke and that of the sheets. If a series of specimens from the different exposures were mixed up it would be impossible to separate those of the dyke from those of the sheets.

A microscopical examination of the specimens likewise shows that they are perfectly identical in composition and structure, chiefly referable to rocks of the dolerite type, but partly to the tholeiite type. I have therefore no doubt that these remarkable appendages to this dyke are truly offshoots from it, and are not to be classed with the general mass of the diabases of central Scotland, which are Lower Carboniferous. The accompanying diagrammatic section (fig. 15) explains what appears to me to be the structure of the ground.

An interesting and important fact remains to be stated in connection with these sheets. They are traversed by some of the other east and west dykes. This is particularly observable in the case of the sheet which extends northwards from the dyke through

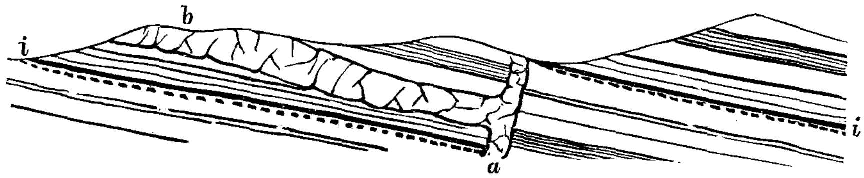


Fig. 15.—Section to show the connection of a Dyke with an Intrusive Sheet, Stirlingshire Coal-field. *a*, Dyke in line of fault; *b*, intrusive sheet travĕrsing and altering the coals; *i*, Slaty-band Ironstone.

the parish of Torphichen. Two well-marked dykes can be seen running westwards among the ridges of the sheet. It is obvious, therefore, that these particular dykes are younger than the sheet. But, as will be shown in the sequel, there is abundant evidence that all the dykes of a district are not of one eruption. The intersection of one eruptive mass by another does not necessarily imply any long interval of time between them. They mark successive, but it may be rapidly successive, manifestations of volcanic action. Hence the cutting of the sheets by other dykes does not seem to me to invalidate the identification of these sheets as extravasations from the great dyke by which they are bounded.

§ 14. Intersections of Dykes—Repeated Dykes in the same Line of Fissure.

Innumerable instances may becited, where one dyke or one set of dykes cuts across another. To some of these I shall refer in discussing the data for estimating the relative age of dykes. In considering the intersection from the point of view of geological structure, we are struck with the clean sharp way in which it so generally takes place. The rents into which the younger dykes have been injected seem, as a rule, not to have been sensibly influenced in width or direction by the older dykes, but go right across them. Hence the younger dykes retain their usual breadth and trend (fig. 16). The most interesting examples are those in which one dyke runs along another, as may occasionally be observed in the west of Scotland.* In these cases, which are to be distinguished from those where the whole may be really a portion of one original slowly cooling mass, the central dyke differs sufficiently in texture and structure to be discrimin-

* Macculloch figured an example from Strathaird, *Western Islands*, pl. xviii. fig. 1. Mr Clough has found some good instances in south-eastern Argyleshire.

ated from that which it has invaded. Its rock is generally rather fine-grained, sometimes decidedly porphyritic, and in many cases is a true basalt. Where it is broad enough to show the difference between margin and centre, its outer edges present the usual finer grain. There can be no doubt that the older dyke has been actually split open, and fresh eruptive material has risen along the fissure.

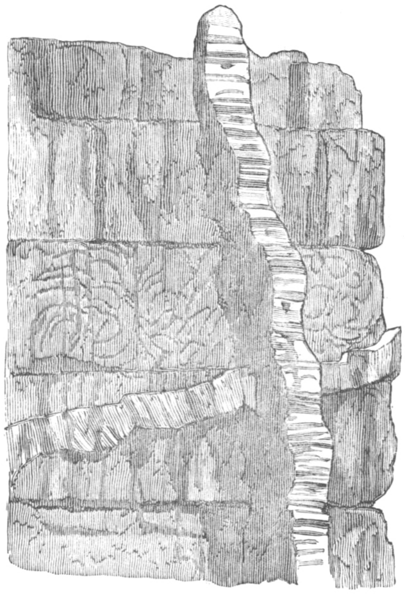


FIG. 16.—Intersection of Dykes in bedded basalt, Caliach Point, Mull.

If the subterranean movements were energetic enough to split up an already consolidated dyke, so as to allow of the renewed uprise of molten material between the separated portions, we may believe that much more frequently the opening would be effected not along the middle of the dyke, but between the dyke and one of its fissure walls. I have observed examples of this structure in the Western Islands, and Mr CLOUGH has recently found a number in Argyleshire. If the section is limited in extent, we may be unable to determine which is the older of the two parallel bands of igneous rock, though the fact that they present to each other the usual fine-grained edge due to more rapid cooling, shows that they are not one but two dykes belonging to distinct eruptions. So far as I have noticed, where one of the dykes can be continuously traced for a considerable distance, the other is short, and cannot be recognised at other exposures of the more continuous one. I infer that the shorter one is the younger of the two.

§ 15. CONTACT-METAMORPHISM OF THE DYKES.

Another anticipation which a geologist might naturally entertain is, that these abundant intrusions of igneous rock should be accompanied with plentiful evidence of contact-metamorphism along their flanks. But in actual fact, evidence of any serious amount of alteration is singularly scarce. A slight induration of the rocks on either side of a dyke is generally all the change that can be detected.

Some of the larger dykes, however, show more marked metamorphism, the nature of which is chiefly determined by the chemical composition of the rock affected. The most pronounced alteration is that which has been superinduced on carbonaceous strata, and particularly on seams of coal. In the Ayrshire coal-field the alteration of the coal extends sometimes 150 feet from the dyke, the extent of the change depending not merely on the mass of the igneous rock, but on the nature of the coal, and possibly on other causes. Close to a dyke, coal passes into a kind of soot or cinder, but sometimes assumes the form of a finely columnar coke.* Shales are converted into a hard flinty substance that breaks with a conchoidal fracture and rings under the hammer. Fire-clay is baked into a

* Explanation of Sheet 22, *Geol. Survey Scotland*, p. 26.

porcelain-like material. Limestone is changed for a few inches into marble. Sandstones are indurated into a kind of quartzite, sometimes assume a columnar structure (the columns being directed away from the dyke-walls), and for several feet or yards have their yellow or red colours bleached out of them. The granite of Ben Cruachan where quarried on Loch Awe, as I am informed by Mr J. S. GRANT WILSON of the Geological Survey, is traversed by a basic dyke, and for a distance of about 20 feet is rendered darker in colour, becomes granular, and cannot be polished and made saleable.

These, however, are the extremes of contact-metamorphism by the Tertiary basic dykes. Let any geologist visit the Lias district of Skye, and he will not fail to be surprised at the almost entire absence of alteration in circumstances where he would have expected to find it. The dark shales, though ribbed across with hundreds of dykes, are sometimes hardly even hardened, and the limestones are not rendered in any appreciable degree more crystalline even up to the very margin of the intrusive rock. Where the igneous material has been thrust between the strata in sheets, it has produced far more general and serious metamorphism than when it occurs in the form of dykes. The famous rock of Portrush, which was once gravely cited as an example of fossiliferous basalt, is a good illustration of the way in which Lias shale is porcellanised when the intruded igneous material has been thrust between its planes of bedding.

In connection with the metamorphism superinduced by dykes, reference may be made to the curious alteration which they themselves have sometimes undergone where they have invaded a carbonaceous shale or coal. The igneous rock loses its dark colour and obviously crystalline structure, and becomes the pale-yellow or white, dull, earthy substance known to geologists as "white trap." The chemical changes involved in this alteration have been described by Sir I. LOWTHIAN BELL.* Dr STECHER has also discussed the the alterations traceable by the aid of the microscope.†

§ 16. RELATION OF DYKES TO THE GEOLOGICAL STRUCTURE OF THE DISTRICTS WHICH THEY TRAVERSE.

In no respect do the Tertiary basic dykes stand more distinguished from all the other rocks of this country than in their extraordinary independence of geological structure. The successive groups of Palæozoic and Mesozoic strata follow each other in approximately parallel bands, which run obliquely across the island from south-west to north-east. The most important lines of fault take the same general line. The contemporaneously included igneous rocks follow, of course, the trend of the stratified deposits among which they lie, and even the intrusive eruptive rocks tend to group themselves along the general strike of the whole country. But the Tertiary dykes have their own independent direction, to which they adhere amid the extremest diversities of geological arrangement.

* *Proc. Roy. Soc.*, xxiii. (1875) p. 543.

† Tschermak's *Mineralogische Mittheilungen*, ix. (1887) p. 145; *Proc. Roy. Soc. Edin.*, 1888. Dr STECHER'S investigation is based upon a series of specimens from the intrusive (Carboniferous) rocks of the basin of the Firth of Forth, and has reference both to the phenomena of contact-metamorphism and the alteration of the eruptive rock; but these changes belong to the Carboniferous period.

In the first place, the dykes intersect nearly the whole range of the geological formations of the British Islands. In the Outer Hebrides and north-west Highlands, they rise through the most ancient Archæan gneisses, and through the red (Torridon) sandstones, which may be older than any of the Cambrian rocks of Wales. In the south of Scotland and north of England, they traverse the various subdivisions of the Lower and Upper Silurian system. In the southern Highlands, they pursue their course across the gnarled and twisted schists of the younger crystalline series. In the basins of the Tay, Forth, and Clyde they cross the plains and ridges of the Old Red Sandstone, with its deep pile of intercalated volcanic rocks. In central Scotland, and the northern English counties, they occur abundantly in the Carboniferous system, and have destroyed the seams of coal. In Cumberland and Durham, they traverse the Permian and Trias groups. In Yorkshire, and along the west of Scotland, they are found running through Jurassic strata. In Antrim, they intersect the Chalk. Both in the north of Ireland, and all through the chain of the Inner Hebrides, they abound in the great sheets and bosses of Tertiary volcanic rocks. These are the youngest formations through which they rise. But it is deserving of note, that they intersect every great group of these Tertiary volcanic products, so that they include in their number some of the latest known manifestations of eruptive action in the geological history of Britain.

In the second place, in ranging across groups of rock belonging to such widely diverse periods, the dykes must necessarily often pass abruptly from one kind of material and geological structure to another. But, as a rule, they do so without any sensible deviation from their usual trend, or any alteration of their average width. Here and there, indeed, we may observe a dyke to follow a more wavy or more rapidly sinuous or zig-zag course in one group of rocks than in another. Yet, so far as I have myself been able to observe, such sinuosities may occur in almost any kind of material, and are not satisfactorily explicable by any difference of texture or arrangement in the rocks at the surface. No dyke traverses a greater variety of sedimentary formations than that of Cleveland. In the eastern part of its course, it rises through all the Mesozoic beds up to the Cornbrash. Further west it cuts across each of the different subdivisions of the Carboniferous system; and, of course, it must traverse all the older formations which underlie these. But the occasional rapid changes noticeable in its width and direction cannot be referred to any corresponding structure in the surrounding rocks. The Cheviot dyke crosses from the Carboniferous area of Northumberland into the Upper Silurian rocks and Lower Old Red Sandstone volcanic tract of the Cheviot Hills. It then strikes across the Upper Old Red Sandstone of Roxburghshire, and still maintaining the same persistent trend, sweeps westward into the Lower Silurian rocks of the Southern Uplands. Though liable to occasional deviations, these do not seem to have reference to any visible change of structure in the adjacent formations. Again, some of the great dykes at the head of Clydesdale furnish striking illustrations of entire indifference to the nature of the rock through which they run. Quitting the Lower

Silurian uplands, they keep their line across Upper Silurian, Old Red Sandstone and Carboniferous rocks, and through large masses of eruptive material.

In the third place, not only are the dykes not deflected by great diversities in the lithological character of the rocks which they traverse, they even cross without deviation some of the most important geological features in the general framework of the country. Some of the Scottish examples are singularly impressive in this respect. Those which strike north-westward from the uplands of Clydesdale cross without deflection the great boundary-fault which, by a throw of several thousand feet, brings the Lower Old Red Sandstone against the Lower Silurian rocks. They traverse some large faults in the valley of the Douglas coal-field, pass completely across the axis of the Haughshaw Hills, where the Upper Silurian rocks are once more brought up to the surface, and also the long felsite ridge of Priesthill. The dykes in the centre of the kingdom maintain their line across some of the large masses of igneous rock that protrude through the Carboniferous system. Further north, the dykes of Perthshire cut across the great sheets of volcanic material that form the Ochil Hills, as well as through the piles of sandstone and conglomerate of the Lower Old Red Sandstone, and then go right across the boundary-fault of the Highlands, to pursue their way in the same independent manner through grit, quartzite, or mica-schist, and across glen and lake, moor and mountain.

No one can contemplate these repeated examples of an entire want of connection between the dykes and the nature and arrangement of the rocks which they traverse without being convinced that the lines of vent up which the material of the dykes rose were not, as a rule, old fractures in the earth's crust, but were fresh fissures, opened across the course of the older dislocations and strike of the country by the same series of subterranean operations to which the uprise of the molten material of the dykes was also due.

In the fourth place, the dykes for the most part are not coincident with lines of fault. After the examination of hundreds of dykes in all parts of the country, and with all the help which bare hill-sides and well-exposed coast sections can afford, I can almost reckon on my fingers the number of instances where dykes have availed themselves of lines of fault. Some of these will be immediately cited. To whatever cause we may ascribe the rupture of the solid crust of the earth, which allowed of the rise of molten rock to form the dykes, there can be no doubt that it was not generally attended with that displacement of level on one or both sides of the dislocation, which we associate with the idea of a fault. Nowhere can this important part of dyke-structure be more clearly illustrated than along the Cleveland dyke, where the igneous rock rises through almost horizontal Jurassic strata and gently inclined Coal Measures (figs. 7 and 8). Besides the localities already cited, mining operations both for coal and for the Liassic ironstone have proved over a wide area that the dyke has not risen along a line of fault. Again, in Skye, Raasay, Eigg, and other parts of the west coast, where Jurassic strata and the horizontal basalts of the plateaux are plentifully cut through by dykes, the same beds may be seen on the same level on either side of them.

In the fifth place, while complete indifference to geological structure is the general rule among the dykes, instances do occur in which the molten material has found its way upward along old lines of rupture. Most of such instances are to be found in districts where previously existing faults happened to run in the same general direction as that followed by the dykes. These lines of fracture would naturally be reopened by any great earth-movements acting in their direction, and would afford ready channels for the ascent of the lava. Yet it is curious that, even when their trend would have suited the line of the dykes, they have not been more largely made use of for the purpose of relief. Some of the best examples of the coincidence of dykes with pre-existing faults in the same direction are to be found in the Stirlingshire coal-field. The dyke that runs from Torphichen for 23 miles to Cadder occupies a line of fault which at Slamannan has a down-throw of more than 70 fathoms. The next dyke further south has also risen along an E. and W. fault.

But other examples may be observed where pre-existing fissures have served to deflect dykes from their usual line of trend. Thus the Cleveland dyke, after crossing several faults in the Coal-Measures, at last encounters one near Cockfield Fell, which lies obliquely across its path. Instead of crossing this fault it bends sharply round a few points south of west, and after keeping along the southern flank of the fault for about a mile, sinks out of reach. Some of the Scottish examples are more remarkable. One of the best of them occurs in the Sanquhar coal-field, where a dyke runs for two miles and a half along the large fault that here brings down the Coal-Measures against the Lower Silurian rocks. At the north-western end of the basin, this fault makes an abrupt bend of 60° to W.S.W., and the dyke turns round with it, keeping this altered course for a mile and a half, when it strikes away from the fault, crosses a narrow belt of Lower Silurian rocks, and finds its way into the parallel boundary fault which defines the north-western margin of the Silurian rocks of the Southern Uplands.

Some of the Perthshire dykes, where they reach the great boundary-fault of the Highlands, present specially interesting features. There can be no doubt that this dislocation is one of the most important in the general framework of the British Isles. We have not yet been able to ascertain definitely how much rock has been actually displaced by it. But the fact that in one place the beds of Old Red Sandstone are thrown on end for some two miles back from it, shows that it must be a very powerful fracture. Here, therefore, if anywhere, we might confidently anticipate either an entire cessation of the dykes, or at least a complete deflection of their course. It would require, we might suppose, a singularly potent dislocation to open a way for the ascent of the lava through such crushed and compressed rocks, and still more to prolong the general line of fracture on either side of the old fault. Two great dykes, about half a mile apart, run in a direction a little S. of W. across the plain of Strathearn. Passing to the south of the village of Crieff, they hold on their way until they reach the highly-inclined beds of sandstone and conglomerate which here lean against the Highland fault in Glen Artney. They then turn round towards S.W., and run up the glen along the strike of the beds, keeping approximately parallel to the fault for about three miles, when they both strike across the fault, and pursue a W.S.W. line through the contorted crystalline rocks of the Highlands. About two miles south, another dyke continues its normal course across the belt of upturned Old Red Sandstone; but when it reaches the fault it bends round and follows the line of dislocation, sometimes coinciding with, sometimes crossing or running parallel with that line at a short distance (see fig. 12).

Mr Clough has supplied me with notes of some remarkable examples recently observed

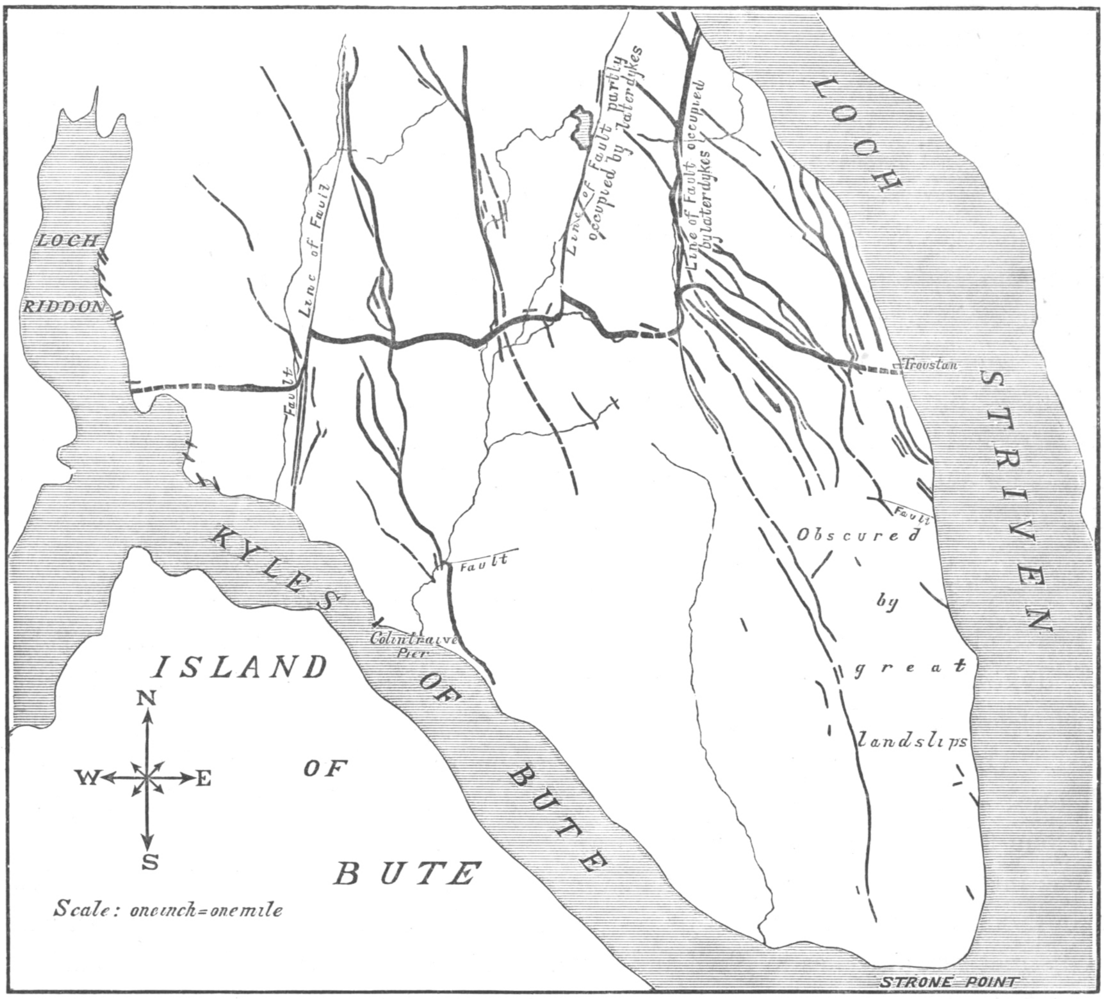


Fig. 17.—Map of the chief Basic Dykes between Lochs Riddon and Striven (C. T. Clough). The large E. and W. dyke is a continuation of that which reaches the shore of the Firth of Clyde at Dunoon.

by him in eastern Argyleshire, where broad bands of basalt or other allied rock run in a N. and S. direction, and are formed by the confluence of N.W. and S.E. or N.N.W. and S.S.E. dykes, where they are drawn into a line of fault. These broad bands, he says, are not usually traceable for more than a mile or so, for the dykes of which they are made up will not be diverted from their regular paths for more than a certain distance, so that one by one the dykes leave the compound band to pursue their normal course. He adds, that the occasional great thickness of those compound bands depends partly on the size and partly on the number of separate dykes that are diverted into the line of transverse fissure; for, where the fissure crosses an area with fewer N.W. dykes, the band becomes thinner or ceases altogether.

In some rare cases, the dykes have been shifted by more recent faults. I shall have occasion to show that faults of several hundred feet have taken place since the Tertiary basalt-plateaux were formed. There is therefore no reason why here and there a fault with a low hade should not have shifted the outcrop of a dyke. But the fact remains that, as a general rule, the dykes run independently of faults even where they approach closely to them. Mr CLOUGH has observed some interesting cases in south-eastern Argyleshire, where the apparent shifting of a dyke by faults proves to be deceptive, and where the dyke has for short distances merely availed itself of old lines of fracture. One of the most remarkable of these is presented by the large dyke which runs westward from Dunoon. No fewer than three times, in the course of four miles between Lochs Striven and Riddon, Mr CLOUGH has found this dyke to make sharp changes of trend nearly at right angles to its usual direction, where it encounters N. and S. faults (fig. 17). It would be natural to conclude that these changes are actual dislocations due to the faults. But this careful observer has been able to trace the dyke in a very attenuated and uncrushed form along some of these cross faults, and thus to prove that the faults are of older date, but that they have modified the line of the long E. and W. fissure up which the material of the dyke ascended.

§ 17. DATA FOR ESTIMATING THE GEOLOGICAL AGE OF THE DYKES.

I have already assigned reasons for regarding the system of E. and W. or S.E. and N.W. dykes as belonging to the Tertiary volcanic period in the geological history of the British Islands. But I have no evidence that they were restricted to any part of that period. On the contrary, there is every reason to consider the uprise of the earliest and latest dykes to have been separated by a protracted interval. That they do not all belong to one epoch I shall now proceed to prove.

The intersection of one dyke by another furnishes an obvious criterion of relative age. MACCULLOCH drew attention to this test, and stated that it had enabled him to make out two distinct sets of dykes in Skye and Rum. But he confessed that it failed to afford any information as to the length of the interval of time between them.* It is not always so easy as might be thought to make sure which of two intersecting dykes is the older. We have to look for the finer-grained marginal strip at the edge of a dyke, which, where traceable across another dyke, marks at once their relative age. The cross joints of the two dykes also run in different directions. It is obvious that in the case of two such dykes, no longer interval need have elapsed between their successive production than was needed for the solidification and assumption of a joint-structure by the older one before the younger broke through it. They may both belong to one brief period of volcanic activity. But when we pass to a series of dykes traversing a considerable district of country, and

* *Trans. Geol. Soc.*, iii. p. 75.

find that those which run in one direction are invariably cut by those which run in another, the inference can hardly be resisted that they do not belong to the same eruption, but mark successive epochs of volcanic energy. An excellent example of this kind of evidence is furnished by Mr CLOUGH from eastern Argyleshire. The east and west dykes in that district are undoubtedly older than those which run in a N.N.W. direction (fig. 17). The latter are by far the most abundant, and are on the whole much narrower, less persistent, and finer in grain. On the opposite coast of the Clyde, a similar double set of dykes may be traced through Renfrewshire, those in an east and west direction being comparatively few, while the younger N.N.W. series is well developed. The great sheets or "sills" connected with one of the Stirlingshire dykes, already described, appear to me to furnish similar evidence in the younger dykes which run through them. And this evidence is peculiarly valuable, for it shows a succession even among adjacent dykes which all run in the same general direction.

But in all these cases it is obvious that we have little indication of the length of time that intervened between the successive uprise of the dykes. In Skye, however, we meet with more definite evidence that the interval must have been in some cases a protracted one. In a paper published as far back as the year 1857,* I showed that the basic dykes of Strath in Skye were of two ages; that one set had been erupted before the appearance of the so-called "syenite" of that district, and was cut off by the latter rock; and that the other had arisen after the "syenite" which it intersected. Recent re-examination has enabled me to confirm and extend this observation. The granitoid eruptions of the Inner Hebrides are marked by so varied a series of rocks, and so complex a geological structure, that they may, with some confidence, be regarded as having occupied a considerable interval of geological time. Yet we find that this episode in the volcanic history was both preceded and followed by the extravasation of basic dykes. I have been unable to make out any appreciable petrographical difference between the two sets of dykes. But for the evidence of the granophyre, they would unquestionably be all classed together as one series.

Let me add one further piece of evidence to prove that some of the dykes go back to a remote part of the volcanic history of Tertiary time in Britain. The Scuir of Eigg, to which fuller reference will be made in a later part of this memoir, is formed of a mass of pitchstone, which has filled up an ancient valley eroded out of the terraced basalts of the plateaux. At both ends of the ridge, these basalts are seen to be traversed by dykes that are abruptly cut off by the shingle of the old river-bed which the pitchstone has occupied (fig. 63). It is thus evident that, though these dykes are younger than the plateau-basalts, they are much older than the excavation of the valley out of these basalts, and still older than the eruption of pitchstone. The latter rock probably belongs to the close of the period of acid eruptions just referred to, and we have seen that abundant dykes were extruded after most of the acid rocks had appeared.

It is certain, therefore, that the dykes which in Britain form part of the great Tertiary

* *Quart. Jour. Geol. Soc.*, xiv. p. 1.

volcanic series, were not all produced at one epoch, but belong to at least two (and possibly to many more) episodes in one long volcanic history. As they rise through every member of that series of rocks (save the pitchstones), some of them must be among the very latest records of the prolonged volcanic activity. But, on the other hand, some may go back to the beginning of the Tertiary volcanic period.

§ 18. Origin and History of the Dykes.

Reference has already been made to the doubt expressed by Macculloch whether the dykes of Skye had been filled in from above or from below. That the dykes of the country as a whole were supplied from above, was the view entertained and enforced by Boué. He introduces the subject with the following remarks:—"Scotland is renowned for the number of its basaltic veins, which gave Hutton his ideas regarding the injection of lava from below; but, as the greatest genius is not infallible, and as volcanic countries present us with examples of such veins arising evidently from accidental fissures that were filled up by currents of lava which moved over them, and as the Scottish instances are of the same kind, we regard it as infinitely probable that all these veins have been formed in the same way, notwithstanding the enormous denudation which this supposition involves; and that only rarely do cases occur where they have been filled laterally or in some other irregular manner." * I need not say that this view, which, except among Wernerians, had never many supporters, has long ago been abandoned and forgotten. There is no longer any question that the molten material came from below.

1. In discussing the history of the dykes, we are first confronted with the problem of the formation of the fissures up which the molten material rose. From what has been said above regarding the usual want of relation between dykes and the nature and arrangement of the rocks which they traverse, it is, I think, manifest that the fissures could not have been caused by any superficial action, such as that which produces cracks of the ground during earthquake-shocks. The fact that they traverse rocks of the most extreme diversities of elasticity, structure, and resistance, and yet maintain the same persistent trend through them all, shows that they originated far below the limits to which the known rocks of the surface descend. We have seen that in the case of the Cleveland dyke, the fissure can be proved to be at least some three miles deep. But the seat of origin of the rents no doubt lay much deeper down within the earth's crust.

It is also evident that the cause which gave rise to these abundant fissures must have been quite distinct from the movements that produced the prevalent strike and the main faults of this country. From early geological time, as is well known, the movements of the earth's crust, beneath the area of Britain, have been directed in such a manner as to give the different stratified formations a general north-east and south-west strike, and to dislocate them by great faults with the same average trend. But the fissures of the Tertiary dykes run obliquely and even at a right angle across this prevalent older series

* *Essai Geologique sur l'Ecosse*, p. 272.

of lines, and are distinct from any other architectonic feature in the geology of the country. They did not arise therefore by a mere renewal of some previous order of disturbances, but were brought about by a new set of movements to which it is difficult to find any parallel in the earlier records of the region.*

We have further to remember that the fissures were not produced merely by one great disturbance. The evidence of the dykes proves beyond question that some of them are earlier than others, and hence that the cause to which the fissures owed their origin came into operation more than once during the protracted Tertiary volcanic period. One of the most instructive lessons in this respect is furnished by the huge eruptive masses of gabbro and granitoid rocks in Skye. These materials have been erupted through the plateau-basalts. The granitoid bosses are the younger protrusions, for they send veins into the gabbros; but their appearance was later than that of some of the dykes and older than that of others. Nevertheless, the latest dykes maintain the usual north-westerly trend across the thickest masses both of the gabbro and the granophyre. Thus we learn that, even after the extrusion of thousands of feet of such solid crystalline igneous rocks, covering areas of many square miles, the fissuring of the ground was renewed, and rents were opened through these new piles of material. From the evidence of the dykes also, we learn that the general direction of the fissures remained from first to last tolerably uniform. Here and there indeed, where one set of dykes traverses another, as in the basin of the Clyde, we meet with proofs of a deviation from the normal trend. But it is remarkable that the very youngest dykes which pierce the eruptive bosses of the Inner Hebrides rose in fissures that were opened in the normal north-westerly line through these great protrusions of basic and acid rock.

Such a gigantic system of parallel fissures points to great horizontal tension of the terrestrial crust over the area in which they were developed. HOPKINS, many years ago, discussed from the mathematical side the cause of the production of such fissures.† He assumed the existence of some elevatory force acting under considerable areas of the earth's crust at any assignable depth, either with uniform intensity at every point, or with a somewhat greater intensity at particular points. He did not assign to this force any definite origin, but supposed it "to act upon the lower surface of the uplifted mass through the medium of some fluid, which may be conceived to be an elastic vapour, or, in other cases, a mass of matter in a state of fusion from heat." ‡ He showed that such an upheaving force would produce in the affected territory a system of parallel longitudinal fissures, which, when not far distant from each other, could only have been formed simultaneously, and not successively; that each fissure would begin not at the surface, but at some depth below it, and would be propagated with great velocity; that there would be more fissures at greater than at lesser depths, many of them never reaching the surface; that they would be of approximately uniform width, the mean width tending

* The only other known example of such a dyke-structure is that of the Pre-Cambrian series of dykes in the Archæan gneiss of Sutherland.

† *Cambridge Phil. Trans.*, vi. (1835) p. 1.

‡ *Op. cit.*, p. 10.

to increase downwards; that continued elevation might increase these fissures, but that new fissures in the same direction would not arise in the separated blocks which would now be more or less independent of each other; that subsequent subsidences would give rise to transverse fissures, and by allowing the separated blocks to settle down would cause irregularities in the width of the great parallel fissures. He considered also the problem presented by those cases where the ruptures of the terrestrial crust have been filled with igneous matter, and now appear as dykes. "The results above obtained," he says, "will manifestly hold equally, whether we suppose the uplifted mass acted upon immediately through the medium of an elastic vapour or by matter in a state of fusion in immediate contact with its lower surface. In the latter case, however, this fused matter will necessarily ascend into the fissures, and if maintained there till it cools and solidifies, will present such phenomena as we now recognise in dykes and veins of trap." *

The existence of a vast lake or reservoir of molten rock under the fissure-region of Britain is demonstrated by the dykes. But, if we inquire further what terrestrial operation led to the uprise of so vast a body of lava towards the surface in older Tertiary time, we find that as yet no satisfactory answer can be given.

2. The rise of molten rock in thousands of fissures over so wide a region is to my mind by far the most wonderful feature in the history of volcanic action in Britain. The great plateaux of basalt, and the mountainous bosses of rock by which they have been disrupted, are undoubtedly the most obvious memorials of Tertiary volcanism. But, after all, they are merely fragments restricted to limited districts. The dykes, however, reveal to us the extraordinary fact that, at a period so recent as older Tertiary time, there lay underneath the area of Britain a reservoir or series of reservoirs of lava, the united extent of which must have exceeded 40,000 square miles.

That the material of the dykes rose in general directly from below, and was not injected laterally along the open fissures, cannot be doubted. The narrowness of these rents, and their enormous relative length, make it physically impossible that molten rock could have moved along them for more than a short distance. The homogeneous character of the rock, the remarkable scarcity of any broken-up consolidated fragments of it immersed in a matrix of different grain, the general uniformity of composition and structure from one end of a long dyke to another, the spherical form of the amygdules, the usual paucity of fragments from the fissure walls—all point to a quiet welling of the lava upward. Over the whole of the region traversed by the dykes, from the hills of Yorkshire and Lancashire to the remotest Hebrides, molten rock must have lain at a depth, which, in one case, we know to have exceeded three miles, and which was probably everywhere considerably greater than that limit.

Forced upwards, partly perhaps by pressure due to terrestrial contraction and partly by the enormous expansive force of the gases and vapours absorbed within it, the lava rose in the thousands of fissures that had been opened for it in the solid overlying crust. That in most cases its ascent terminated short of the surface of the ground may reasonably

* *Op. cit.*, p. 69.

be inferred. At least, we know, that many dykes do not reach the present surface, and that those which do have shared in the enormous denudation of the surrounding country. That even in the same dyke the lava rose hundreds of feet higher in one place than at another is abundantly proved. When, however, we consider the vast number of dykes that now come to the light of day, and reflect that the visible portions of some of them differ more than 3000 feet from each other in altitude, we can hardly escape the conviction that it would be incredible that nowhere should the lava have flowed out at the surface. Subsequent denudation has undoubtedly removed a great thickness of rock from what was the surface of the ground during older Tertiary time, and hundreds of dykes are now exposed that originally lay deeply buried beneath the overlying part of the earth's crust through which they failed to rise. But some relics, at least, of the outflow of lava might be expected to have survived. I believe that such relics remain to us in the great basalt-plateaux of Antrim and the Inner Hebrides. These deep piles of almost horizontal sheets of basalt, emanating from no great central volcanoes, but with evidence of many small local vents, appear to me to have proceeded from dykes that reached the highest level, and from which orifices, communicating with the surface of the ground, allowed the molten material to flow out in successive streams with occasional accompaniments of fragmentary ejections. The structure of the basalt-plateaux, and their mode of origin, will form the subject of the next division of this paper.

We can hardly suppose, however, that the lava flowed out only in the western region of the plateaux. Probably it was most frequently emitted and accumulated to the greatest depth in that area. But over the centre of Scotland and north of England there may well have been many places where dykes actually communicated with the outer air, and allowed their molten material to stream out over the surrounding country. The disappearance of such outflows need cause no surprise, when we consider the extent of the denudation which many dykes demonstrate. I have elsewhere shown that all over Scotland there is abundant proof that hundreds and even thousands of feet of rock have been removed from parts of the surface of the land since the time of the uprise of the dykes.* The evidence of this denudation is singularly striking in such districts as that of Loch Lomond, where the difference of level between the outcrop of the dykes on the crest of the ridges and in the bottom of the valley exceeds 3000 feet. It is quite obvious that, had the deep hollow of Loch Lomond lain as it now does in the pathway of these dykes, the molten rock, instead of ascending to the summits of the hills, would have burst out on the floor of the valley. We are, therefore, forced to admit that a deep glen and lake-basin have been in great measure hollowed out since the time of the dyke. If a depth of many hundreds of feet of hard crystalline schists could have been removed in the interval there need be no difficulty in understanding that by the same process of waste, many sheets of solid basalt have been gradually stripped off the face of central Scotland and northern England.

* *Scenery of Scotland*, 2d edit. (1887), p. 149. But see the remarks already made (p. 55) on the curious coincidence sometimes observable between the upper limit of a dyke and the overlying inequalities of surface.

This association of dykes with the out-welling of lava and with the accumulation of deep and extensive volcanic plateaux, is paralleled in other parts of the world. The description by Mr G. T. CLARK of the dykes connected with the vast basaltic sheets of the Bombay Presidency corresponds almost exactly with that which I have given of those of this country. The Indian, like the British, examples occur in great numbers, rising through every rock in the district up to the crests of the Ghauts, 4000 feet above the sea. They vary from one or two to 10, 20, 40, and even occasionally 100 or 150 feet in width, and are often many miles in length. They observe a general parallelism in one average direction, and show no perceptible difference in character even when traced up to elevations of 3000 and 4000 feet.*

To this and other areas, where horizontal sheets of basalt cover enormous tracts of country with no great central volcanic cones from which the material could have come, fuller reference will be made in the next division of this paper, which treats of the basalt-plateaux of the British Islands.†

II. THE VOLCANIC PLATEAUX.

We have now to consider the structure and history of those volcanic masses which, during Tertiary time, were ejected to the surface within the area of the British Islands, and now remain as extensive basalt-plateaux. Short though the interval has been in a geological sense since these rocks were erupted, it has been long enough to allow of very considerable movements of the ground and of enormous denudation. Hence the superficial records of Tertiary volcanic action have been reduced to a series of broken and isolated fragments. I have already stated that no evidence now remains to show to what extent there were actual superficial outbursts of volcanic material over the rest of the dyke-region of Britain, and the subsequent waste of the surface has been so enormous that various lava-fields may quite possibly have stretched across parts of England and Scotland, from which they have since been wholly stripped off, leaving behind them only that wonderful system of dykes from which their molten materials were supplied.

There can be little doubt, however, that whether or not other Phlegrean fields extended over portions of the country whence they have since been worn away, the chief volcanic tract lay to the west in a broad and long depression that stretched from the south of Antrim to the Minch. From the southern to the northern limit of the fragmentary lava-fields that remain in this depression is a distance of some 250 miles, and the average breadth of ground within which these lava-fields are preserved may be taken to range from 20 to 50 miles. If, therefore, the sheets of basalt and layers of tuff

* *Quart. Jour. Geol. Soc.*, xxv. (1869) p. 163.

† It is interesting to note that in the great paper on Physical Geology already cited, HOPKINS considered the question of the outflow of lava from the fissures which he discussed. "If the quantity of fluid matter forced into these fissures," he says, "be more than they can contain, it will, of course, be ejected over the surface; and if this ejection take place from a considerable number of fissures, and over a tolerably even surface, it is easy to conceive the formation of a bed of the ejected matter of moderate and tolerably uniform thickness, and of any extent" (*op. cit.*, p. 71).

extended over the whole of this strip of country, they covered a space of some 7000 or 8000 square miles. But they were not confined to the area of the British Islands. Similar rocks rise into plateaux in the Faroe Islands, and it may reasonably be conjectured that the remarkable submarine ridge which extends thence to the north-west of Scotland, and separates the basin of the Atlantic from that of the Arctic Ocean, is partly at least of volcanic origin. And still further north come the extensive Tertiary basaltic plateaux of Iceland, while others of like aspect and age cover a vast area in southern Greenland. Without contending that one continuous belt of lava-streams stretched from Ireland to Iceland and Greenland, we can have no doubt that in older Tertiary time the north-west of Europe was the scene of more widely-extended volcanic activity than showed itself at any other period in the geological history of the whole continent. Possibly, as I have already suggested, the present active vents of Iceland and Jan Mayen are the descendants in uninterrupted succession of those that supplied the materials of the Tertiary basaltic plateaux, the volcanic fires slowly dying out from south to north. But so continuous and stupendous has been the work of denudation in these northern regions, where winds and waves, rain and frost, floe-ice and glaciers reach their highest level of energy, that the present extensive sheets of igneous rock can be regarded only as magnificent relics, the grandeur of which furnishes some measure of that which characterised the last episode in the extended volcanic records of Britain.

The long and wide western valley in which the basalt-plateaux of this country were accumulated seems, from a remote antiquity, to have been a theatre of considerable geological activity. There are traces of some such valley or depression even back in the period of the Torridon sandstone of the north-west which was laid down in it between the great ridge of the Outer Hebrides and some other land to the east. The Lower Old Red Sandstone of Lorne may represent the site of one of its lakes. The Carboniferous rocks, which run through the north of Ireland, cross into Cantyre, and are found even as far north as the Sound of Mull, mark how, in later Palæozoic time, the same strip of country was a region of subsidence and sedimentation. During the Mesozoic ages, similar operations were continued; the hollow sank several thousand feet, and Jurassic strata to that depth filled it up. Before the Cretaceous period, underground movements had disrupted and irregularly upheaved the Jurassic deposits, and prolonged denudation had worn them away, so that when the Cretaceous formations came to be laid down on the once more subsiding depression, they were spread out with a strong unconformability on everything older than themselves, resting on many successive horizons of the Jurassic system, and passing from these over to the submerged hill-sides of the crystalline schists. Yet again, after the accumulation of the Chalk, the sea-floor along the same line was ridged up into land, and the Chalk, exposed to denudation, was deeply trenched by valleys, and entirely removed from wide tracts which it once covered.

It was in this long broad hollow, with its memorials of repeated subsidences and upheavals, sedimentation and denudation, that the vigour of subterranean energy at last showed itself in volcanic outbreaks, and in the gradual piling up of the materials of the basalt-plateaux. So far as we know, these outbursts were subærial. At least no trace of any marine deposit has yet been found even at the base of the pile of volcanic rocks. Sheet after sheet of lava was poured out, until several thousand feet had accumulated, so as perhaps to fill up the whole depression, and once more to change entirely the aspect of the region. But the Volcanic period, long and important as it was in the geological history of the country, came to an end. It too was merely an episode during which denudation still continued active, and since which subterranean disturbance and superficial erosion have again transformed the topography. In wandering over these ancient lava-fields, we see on every hand the most stupendous evidence of change. They have been dislocated by faults, sometimes with a displacement of hundreds of feet, and have been hollowed out into deep and wide valleys and arms of the sea. Their piles of solid rock, thousands of feet thick, have been totally stripped off from wide tracts of ground which were once undoubtedly buried under them. Hence, late though the volcanic events are in the history of the land, they are already separated from us by so vast an interval that there has been time for cutting down the wide plateaux of basalt into a series of mere scattered fragments. But the process of land-sculpture has been of the utmost service to geology, for, by laying bare the inner structure of these plateaux, it has provided materials of almost unequalled value and extent for the study of one type of volcanic action.

§ 1. Petrography.

The superficial outbursts of volcanic action during Tertiary time in Britain are represented by a comparatively small variety of rocks. By far the largest area and thickest mass consist of dark basic lavas. In only one locality (Isle of Eigg) has any outflow of acid lava been detected. Between the lava-sheets occasional layers of volcanic and even non-volcanic fragmental rocks occur. The general lithological characters of the whole group of plateau-rocks may here be briefly enumerated.

1. *Lavas.*—In external characters these rocks range from coarsely crystalline varieties, in which the constituent minerals may be more or less readily detected with the naked eye or a field-lens, to dense black compounds in which only a few porphyritic crystals may be microscopically visible. They are easily recognised as pertaining in the vast majority of cases to the great group of the dolerites and basalts. One of their characteristic features is the presence of the ophitic structure, sometimes only feebly developed, sometimes showing itself in great perfection. Many of the rocks are holo-crystalline, but usually show more or less interstitial matter (dolerites); in others the texture is finer, and the interstitial matter more developed (basalts); in no case, so far as I have observed, are there any glassy varieties, which are restricted to the dykes, though in some of the basalts there is a considerable proportion of glassy or incompletely devitrified substance. The felspars are of the characteristic lath-shaped forms, and are usually quite clear and fresh. The augite resembles that of the dykes, occurring sometimes in large plates that enclose the felspars, at other times in a finely granular form. Olivine is frequently not

to be detected, even by green alteration products. Magnetite is sometimes present in such quantity as to affect the compass of the field-geologist. Porphyritic varieties occur with larger crystals of a different form from the laths of the base; but such varieties are, I think, less frequent among the plateau-rocks than among the dykes.

In a few localities, there are found intercalated with the ordinary dark heavy dolerites and basalts certain pale rocks of much lower specific gravity (2·71–2·74). Externally these sheets are dull in texture, sometimes strongly amygdaloidal, sometimes with a remarkable platy structure, which, in the process of weathering, causes them to split up like stratified rocks. Examined with the microscope, they are found to consist almost wholly of felspar in minute laths or microliths, but in none of my specimens sufficiently definite for satisfactory determination. In one of the best slides Dr F. HATCH, in whose hands I placed it, finds that "each lath of this abnormal felspar passes imperceptibly into those adjacent to it; the double refraction being very weak, and the twin-striation, if present, not being traceable." He suggests whether the rock "originally consolidated as a glass, poor in iron and magnesia, the development of the felspar being due to devitrification." * Some of the varieties are amygdaloidal, the cells being filled with epidote, which also appears in the fissures, and sometimes even as a constituent of the rock. To such compounds I do not know that any existing petrographical name is applicable. As they form the upper portion of Ben More, and the tops of some of its neighbours in Mull, I have been in the habit of speaking of them as the "felspathic lavas" or "pale-group" of Ben More, and it will be preferable to use some such vague definition until their true chemical and mineralogical characters have been worked out.

Passing now to the occurrence of the lavas as beds of rock in the plateaux, we find them to present three well-marked types, all of which, however, pass into each other. 1st, Massive and amorphous; 2d, Prismatic; 3d, Amygdaloidal and slaggy.

1. The more coarsely crystalline varieties (dolerites) are apt to occur in thick massive beds, with no definite structure except the usual somewhat irregular joints placed perpendicularly to the upper and under surfaces. In their general aspect, such beds cannot readily be separated from intrusive sheets. But where they are not intrusive, they will generally be found somewhat cellular towards their upper and lower surfaces; while, where intrusive, they are generally more close-grained there than anywhere else. Rocks of this character are less frequent than those of the other two varieties.

2. Prismatic structures are typical of the more compact heavy basalts. A considerable variety is observable in the degree of perfection of their development. Where they are

* In the course of my investigations I have had many hundreds of thin slices cut from the Tertiary volcanic rocks for microscopic determination. These I have myself studied in so far as their microscopic structure appeared likely to aid in the investigation of those larger questions of geological structure in which I was more specially interested. But for their detailed examination I have placed them with Dr HATCH, in whose hands, together with the large series of specimens accumulated by the Geological Survey, they will form the subject of a future memoir on the microscopic petrography of this most interesting group of rocks. He has submitted to me the results of his preliminary examination, and where these offered points of geological import I have availed myself of them by citations in the course of this memoir. Professor JUDD, in a series of valuable papers, has discussed the general petrography of the Tertiary volcanic rocks; *Quart. Jour. Geog. Soc.*, vols. xxxix., xli., xlii.

least definite, the rock is traversed by vertical joints, somewhat more regular and close-set than those in the dolerites, by the intersection of which it is separated into rude quadrangular or polygonal columns. The true prismatic structure is shown in two chief forms. (*a*) The rock is divided into close-fitting parallel, usually six-sided, columns; the number of sides varying, however, from three up to nine. The columns run the whole thickness of the bed, and vary thus from 8 or 10 to 40 or even 80 feet in length. They are segmented by cross joints which sometimes, as at the Giant's Causeway, take the ball and socket form. Occasionally they are curved, as at the well-known Clam-shell cave of Staffa. (*b*) The prisms are much smaller, and diverge in wavy groups crowded confusedly over each other, but with a general tendency upwards. This starch-like aggregation may be observed superposed directly upon the more regular columnar form, as at the Giant's Causeway and also at Staffa.

3. It may often be noticed that, even where the basalt is most perfectly prismatic, it presents a cellular and even slaggy structure at the bottom. The rock that forms the Giant's Causeway, for instance, is distinctly vesicular, the vesicles being drawn out in a general E. and W. direction. The beautifully columnar bed of Staffa is likewise slaggy and amygdaloidal for a foot or so upwards from its base, and portions of this lower layer have here and there been caught up and involved in the more compact material above it. Even the bottom of the confusedly prismatic bed above the columnar one on that island also presents a cellular texture. A similar rock at Ardtun, in Mull, passes upward into a rugged slag and confused mass of basalt blocks, over which the leaf-beds lie. At Loch-na-Mna, in the island of Eigg, one of the basalts presents in places a remarkable streaky structure, due, doubtless, to the arrangement of its component materials during the flow of the still molten rock.

Amygdaloidal structure is more or less well developed throughout the whole series of basalts. But it is especially marked in certain abundant sheets, which, for the sake of distinction, are called amygdaloids. These beds, which form a considerable proportion of the materials of every one of the plateaux, are distinguished by the abundance and large size of their vesicles. In some places, these cavities occupy at least as much of the rock as the solid matrix in which they lie. They have generally been filled up with some infiltrated mineral—calcite, chalcedony, zeolites, &c. The amygdules of the west of Skye and of Antrim have long been noted for their zeolitic enclosures. As a consequence of their cellular texture and the action of infiltrating water upon them, these amygdaloidal beds are always more or less decomposed. Their dull, lumpy, amorphous beds contrast well with the prismatic sheets above and below them, and as they crumble down they are apt to be covered over with vegetation. Hence, on a sea-cliff or escarpment, the green declivities between the prominent columnar basalts usually mark the place of these less durable bands.

Exceedingly slag-like lavas are to be seen among the amygdaloids, immediately preceded and followed by beds of compact black basalt with few or no vesicles. From the manner in which such rocks yield to the weather, they often assume a singularly deceptive resemblance to agglomerates. One of the best examples of this resemblance which have come under my notice is that of the rock on which stands Dunluce Castle, on the north coast of Antrim. Huge rounded blocks of a harder consistency than the rest of the rock project from the surface of the cliffs, like the bombs of a true volcanic agglomerate, while the matrix in which they are wrapped has decayed from around them. But an examination of this matrix will soon convince the observer that it is strongly amygdaloidal, and that the apparent "bombs" are only harder and less cellular portions of it. The contrast between the weathering of the two parts of the rock seems to have arisen from an original variety in the relative abundance of steam-cavities. Another singular instance occurs at the foot of the outlier of Fionn Chro (fig. 51), in the island of Rum. A conspicuous band underlying the basalts there might readily be taken for a basalt-conglomerate. But in this case, also, the apparent matrix is found to be amygdaloidal, and the rounded blocks are really amygdules, sometimes a foot in length, filled or lined with quartz, chalcedony, &c.

A somewhat different structure, in which, however, the appearance of volcanic breccia or agglomerate due to explosion from a vent is simulated, may be alluded to here. The best instance which I have observed of it occurs at the south end of Loch-na-Mna, in the island of Eigg. The basalt above referred to as occurring at this locality shows on its weathered surfaces a remarkable streaky structure that gives rise to prominent thin nearly parallel ribs coincident with the direction of bedding. This arrangement, probably due, as I have said, to the flow of the basalt while still unconsolidated, can hardly be traced with the naked eye on a fresh fracture of the rock, the whole appearing as a black compact basalt. On the weathered faces, the streaky layers may be observed to have been broken up, and their disconnected fragments have been involved in ordinary basalt wherein this flow-structure is not developed, while large blocks and irregular masses are wrapped round in a more decomposing matrix. There can be no doubt that in such cases we see the effects of the disruption of chilled crusts, and the entanglement of the broken pieces in the still fluid lava.

Great variety is to be found in the thickness of different sheets of lava in the plateaux. Some of them are not more than 6 or 8 feet; others reach to 80 or 100 feet, and sometimes, though rarely, to even greater dimensions. In Antrim, the average thickness of the flows is probably from 15 to 20 feet.* In the fine coast-sections at the Giant's Causeway, however, some bands may be seen far in excess of that measurement. The bed that forms the Causeway, for instance, is about 60 or 70 feet thick, and seems to become even thicker further east. Along the great escarpment, 700 feet high, which rises from the shores of Gribon, on the west coast of Mull, there are twenty separate beds, which gives an average of 35 feet for the thickness of each flow. On the great range of sea-precipices, on the west coast of Skye, which present the most stupendous section of the basalts anywhere to be seen within the limits of the British Islands, the average thickness of the beds can be conveniently measured. At the Talisker cliffs some of the

* See Explanation of Sheet 20, *Geol. Survey, Ireland*, p. 11.

flows are not more than 6 or 8 feet; others are 30 or 40 feet. In the vast walls that form the seaward margin of the tableland of Macleod's Tables (fig. 21), fourteen successive beds of basalt can be counted in a vertical section of 400 feet, which is equal to an average thickness of about 28 feet. But some of the basalts are only about 6 feet thick, while others are 50 or 60.

Each bed appears, on a cursory inspection, to retain its average thickness, and to be continuous for a long distance. But I believe that this persistence is in great measure deceptive. It is not often that we can follow the same bed with absolutely unbroken continuity for more than a mile or two. Even in the most favourable conditions, such as are afforded by a bare sea-cliff on which every bed can be seen, there occur small faults, gullies where the rocks are for the time concealed, slopes of débris, and other failures of continuity; while the rocks are generally so like each other, that on the further side of any such interruption, it is not always possible to make sure that we are still tracing the same bed of basalt which we may have been previously following. On the other hand, a careful examination of one of these great natural sections will usually supply us with proofs that, while the bedded character may continue well marked, the

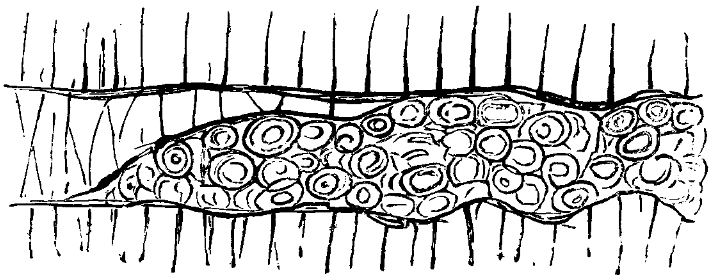


FIG. 18.—Termination of Basalt-beds, Carsaig, Mull.

individual beds die out, and are replaced by others of similar character. On the south coast of Mull, for instance, cases may be observed where the basalt of one sheet abruptly wedges out, and is replaced by that of another. Where both are of the same variety of rock, it requires close inspection to make out the difference between them; but where one is a green, dull, earthy, amorphous amygdaloid, and the other is a compact, black, prismatic basalt, the contrast between the two beds can be recognised from a distance (fig. 18). Again, along the west coast of Skye, the really lenticular character of the beds can be well seen.

In Antrim also, where similar proofs may be obtained, remarkable evidence is presented of the rapid attenuation not of single beds only, but of a whole series of basalts. Thus, at Ballycastle, the group of lavas known as the Lower Basalts, which underlie the well-known horizon of iron-ore, are at least 350 feet thick. But, as we trace them westwards, bed after bed thins out until, a little to the west of Ballintoy, a distance of only about 6 miles, the whole depth of the group has diminished to somewhere about 40 feet. A decrease of more than 300 feet in six miles or 50 feet per mile points to considerable inequalities in the accumulation of the lavas. If the next series of flows came from another vent and accumulated against such a gentle slope, it would be marked by a slight unconformability. Structures of this kind are much rarer than we should expect them to be, considering the great extent to which the plateaux have been dissected and laid open in cliff sections. Near the west end of Glen More, in Mull, I observed a hillside where, as seen from a little distance, one series of basalts appears to be banked up against the edges of another.

A common feature in all the plateaux is the intervention of a red layer between successive sheets of basalt. These red streaks form a striking feature on many sea-cliffs, and emphasise the bedded character of the volcanic series. Examined more closely, the thin red line is found to be a layer of clay or bole which shades into the decomposed top of the bed whereon it lies, and is usually somewhat sharply marked off from that which covers it. This layer has long, and I think correctly, been regarded as due to the atmospheric disintegration of the surface of the basalt on which it occurs, before the eruption of the overlying flow. It varies in thickness from a mere line up to a foot or more, and it passes into the tuffs and clays which are sometimes interposed between the sheets of basalt.

2. *Fragmental Rocks.*—While the plateaux are built up mainly of successive flows of basaltic lavas, they include various intercalations of fragmental materials, which, though of trifling thickness, are of great interest and importance in regard to the light which they cast on the history of the different regions during the volcanic period. I shall enumerate the chief varieties of these rocks here, and give fuller details regarding their stratigraphical relations and mode of occurrence in connection with the succession of beds in each of the plateaux.

a. Volcanic Agglomerates.—Under this name are included all the tumultuous unstratified masses of fragmentary materials which fill eruptive vents in and around the plateaux. The stones vary in size up to blocks several feet in diameter. They consist for the most part of basalts, often highly slaggy and scoriaceous, also fragments of different acid eruptive rocks (generally felsitic in texture), with pieces of the non-volcanic rocks through which the volcanic pipes have been drilled. The paste is granular, dirty-green or brown in colour, and seems generally to consist chiefly of comminuted basalt.

b. Volcanic Conglomerates and Breccias in beds intercalated between the flows of Basalt.—These are of at least three kinds. (*a*) Basalt-conglomerates, composed mainly of rounded and subangular blocks of basalt (or allied basic lava), sometimes a yard or more in diameter, not unfrequently in the form of pieces of rough slag or even of true bombs, embedded in a granular matrix of comminuted basalt-débris. In some cases, the stones form by far the most abundant constituents of the rock, which then resembles some of the coarse agglomerates just described. On the east side of Mull, for example, the slaggy basalts of Beinn Chreagach Mhor are occasionally separated by materials of this character. But such intercalations are seldom more than a few feet or yards in thickness. Their coarseness and repetition on successive horizons show that they accumulated in the near neighbourhood of one or more small vents, from which discharges of fragmentary materials took place at the beginning or at the close of an outflow of lava. More commonly, however, the dirty-green or dark-brown granular matrix exceeds in bulk the stones embedded in it. It has obviously been derived mainly from the trituration of already cooled basalt-masses, and probably also from explosions of the still molten rock in the vents. As in the case of the agglomerates of the vents, pieces of older acid lavas, and still more of the non-volcanic rocks that underlie the plateaux, are found in these bedded conglomerates and breccias. In Antrim and Mull, for instance, fragments of flint and chalk are of common occurrence. A characteristic example of this kind of rock is to be seen forming the platform of the remarkable columnar bed out of which Fingal's Cave, Staffa, has been excavated.

(β) Felsitic Breccia and Conglomerate.—This variety is of rare occurrence, but it is to be seen in a number of localities in the island of Mull. It is composed in great measure of angular fragments of a close-grained flinty felsitic rock, with pieces of quartzite and amygdaloidal basalt, the dull dirty-green matrix appearing to be made up chiefly of basalt-dust.

(γ) Breccias of Non-Volcanic Materials.—These, the most exceptional of all the fragmentary intercalations in the plateaux, consist almost wholly of angular blocks of rocks which are known to underlie the basalts, but with a variable admixture of basalt fragments. They are due to volcanic explosions which shattered the subjacent older crust of rocks, and discharged fragments of these from the vents or allowed them to be borne upwards on an ascending column of basic lava. Pieces of the non-volcanic platform are of common occurrence among the fragmentary accumulations, especially in the lower parts of the plateaux-basalts. But I have never seen so remarkable an example of a breccia of this kind as that which occurs near the summit of Sgurr Dearg, in the east of Mull. The bedded basalt encloses a lenticular band of exceedingly coarse breccia, consisting mainly of angular pieces of quartzite, with fragments of amygdaloidal basalt. In the midst of the breccia lies a huge mass or cake of erupted mica-schist, at least 100 yards long by 30 yards wide, as measured across the strike up the slope of the hill. To the west, owing to the thinning out of the breccia, this piece of schist comes to lie between two beds of basalt. A little higher up, other smaller but still large blocks of similar schist are involved in the basalt, as shown in fig. 19. As the huge cake of mica-schist plunges into the hill, its whole dimensions cannot be seen; but there are visible, at least, 15,000 cubic yards, which must weigh more than 30,000 tons. Blocks of quartzite of less dimensions occur in the basalts on Loch Spelve. There can be no doubt, I think, that these enormous fragments were torn off from the underlying crystalline schists which form the framework of the western Highlands, and were floated upward in an ascending flow of molten basalt. Had the largest mass occurred at or near the base of the volcanic series, its size and position would have been less remarkable. But it lies more than 2000 feet up in the basalts, and hence must have been borne upward for more than that height. A similar but less striking breccia occurs on the south coast of the same island, near Carsaig, made up chiefly of pieces of quartzite and quartz.*

c. Tuffs.—So far as I am aware, all the tuffs intercalated in the basalt-plateaux consist essentially of basic materials, derived from the destruction of different varieties of basalt-rocks, though also containing occasional fragments of older felsitic rocks, as well as pieces of chalk, flint, quartz, and other non-volcanic materials. They are generally dull, dirty-green in colour, but become red, lilac, brown, and yellow, according to the amount and state of combination and oxidation of their ferruginous constituents. They usually contain abundant fragments of amygdaloidal and other basalts. As a rule, they are distinctly stratified, and occur in bands from a few inches to 50 feet or more in thickness. The matrix being soft and much decomposed, these bands crumble away under the action of the weather, and contribute to the abruptness of the basalt-escarpments that so often overlie them.

Where the tuffs become fine-grained and free from embedded stones, they pass into variously-coloured clays. Among these are the "beauxite" and "lithomarge" of Antrim.

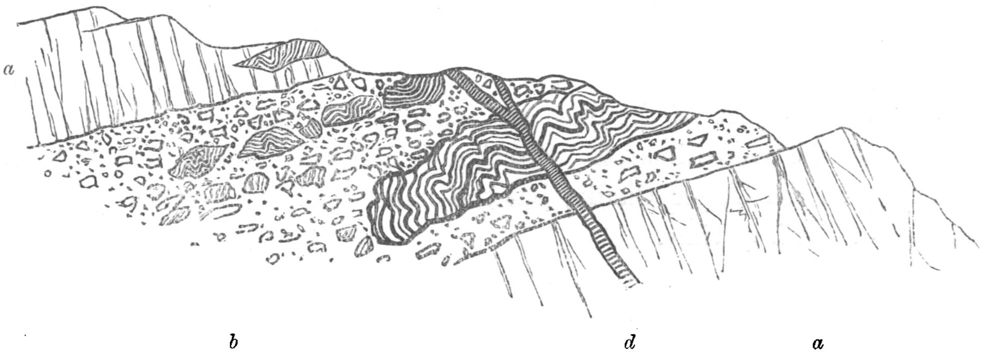


FIG. 19.—Breccia and Blocks of mica-schist, quartzite, &c., lying between bedded Basalts, Isle of Mull.
a,a, Bedded basalts ; *b,* Breccia ; *d,* Basic dyke.

Associated with these deposits in the same district, is a pisolitic hæmatite, which has been proved to occur over a considerable area on the same horizon. Many of the clays are highly ferruginous. The red streaks that intervene between successive sheets of basalt are of this nature (bole, plinthite, &c.). The source of the iron-oxide is doubtless to be traced to the decomposition of the basic lavas during the volcanic period.

d. There occur also grey and black clays and shales, of ordinary sedimentary materials, not infrequently containing leaves of terrestrial plants and remains of insects (leaf-beds), sometimes associated with impure limestones, but more frequently with sandstones and indurated gravels or conglomerates containing pieces of fossil wood. These intercalated bands undoubtedly indicate the action of running water and the accumulation of sediment in hollows of the exposed flows of basalt at intervals during the piling up of the successive lava-sheets that form the plateaux.

The vegetable matter has in some places gathered into lenticular seams of lignite, and

* This is noticed by Mr STARKIE GARDNER, *Quart. Jour. Geol. Soc.*, xliii. (1887) p. 283, note.

even occasionally of black glossy coal. Amber also has been found in the lignite. Where the vegetation has been exposed to the action of intrusive dykes or sheets, it has sometimes passed into the state of graphite.

The remarkable terrestrial flora found in the leaf-beds, and in association with the lignites, was first made known by the descriptions of EDWARD FORBES already referred to, and has more recently been studied and described by HEER, Mr BAILY, and Mr STARKIE GARDNER.* It was regarded by FORBES as of Miocene age, and this view has generally been adopted by geologists. Mr STARKIE GARDNER, however, contends that it indicates a much wider range of geological time. He believes that a succession of floras may be recognised, the oldest belonging to an early part of the Eocene period. Terrestrial plants, it must be admitted, are not always a reliable test of geological age, and I am not yet satisfied that in this instance they afford evidence of such a chronological sequence as Mr GARDNER claims, though I am convinced that the Tertiary volcanic period was long enough to have allowed of the development of considerable changes in the character of the vegetation.

For the purpose of the present paper, however, the precise stage in the geological record, which this flora indicates, is of less consequence than the broad fact that the plants prove beyond all question that the basalts among which they lie were erupted on land during the older part of the long succession of Tertiary periods. Their value in this respect cannot be overestimated. Stratigraphical evidence shows that the eruptions must be later than the Upper Chalk; but the embedded plants definitely limit them to the earlier half of Tertiary time.

§ 2. AREAS OF THE PLATEAUX AND SUCCESSION OF ROCKS IN THEM.

There are four districts in which the original widespread lava-fields have been less extensively eroded than elsewhere, or at least where they have survived in larger and thicker masses. Whether or not each of them was an isolated area of volcanic activity cannot now be determined. Their several outflows of lava may have united into one continuous volcanic tract, and their present isolation may be due entirely to subterranean movements and denudation. There is a certain convenience, however, in treating them separately. They are—1. Antrim; 2. Mull; 3. Small Isles; 4. Skye. To these might be added the Shiant Isles and St Kilda.

1. *Antrim.*†—The largest of the basalt-plateaux of Britain is that which forms so prominent a feature in the scenery and geology of the north of Ireland, stretching from Lough Foyle to Belfast Lough, and from Rathlin Island to beyond the southern margin of Lough Neagh. Its area may be roughly computed at about 2000 square miles. But,

* Mr GARDNER is now describing and illustrating the flora fully for the Palæontographical Society; see vols. xxxviii., xxxix. *et seq.*

† The basalts of Antrim are the subject of an abundant literature. I may refer particularly to the papers of BERGER and CONYBEARE (*Trans. Geol. Soc.*, iii.), the Geological Report of PORTLOCK, and the Explanations of the Sheets of the *Geological Survey of Ireland.*

as its truncated strata rise high along its border, and look far over the low grounds on every side, it must be regarded as a mere fragment of the original volcanic plain. It may be described as an undulating tableland, which almost everywhere terminates in a range of bold cliffs, but which, towards the centre and south, sinks gently into the basin of Lough Neagh. The marginal line of escarpment, however, presents considerable irregularity both in height and form, besides being liable to frequent local interruptions. It is highest on the west side, one of its crests reaching at Mullaghmore, in county Londonderry, a height of 1825 feet. On the north, it sinks down into the valley of the Bann, east of which it gradually ascends, forming the well-known range of cliffs from the Giant's Causeway and Bengore Head to Ballycastle. It then strikes inland, and making a wide curve in which it reaches a height of more than 1300 feet, comes to the sea again at Garron Point. From that headland the cliffs of basalt form a belt of picturesque ground southwards beyond Belfast, interrupted only by valleys that convey the drainage of the interior of the plateau to the North Channel. Above the valley of the Lagan the crest of the plateau rises to a height of more than 1500 feet.

Throughout most of its extent the basalt-escarpment rests on the white limestone or Chalk of Antrim, beneath which lie soft Lias shales and Triassic marls. Here and there, where the substratum of Chalk is thin, the action of underground water in the crumbling shales and marls below it has given rise to landslips. The slopes beneath the base of the basalt are strewn with slipped masses of that rock, almost all the way from Cushendall to Larne, some of the detached portions being so large as to be readily taken for parts of the unmoved rock. On the west side also, a group of huge landslips cumbers the declivities beneath the mural front of Benevenagh.

I have found some difficulty in the attempt to ascertain what was the probable form of surface over which the volcanic rocks of this plateau began to be poured out. The Chalk sinks below the sea-level on the north coast, but, in the outlier of Slieve Gallion, three miles beyond the western base of the escarpment, it rises to a height of 1500 feet above the sea. On the east side also, it shows remarkable differences of level. Thus, below the White Head at the mouth of Belfast Lough, it passes under the sea-level, but only 16 miles to the south, where it crops out from under the basalt, its surface is about 1000 feet above that level. If these variations in height existed at the time of the outpouring of the basalt, the surface of the ground over which the eruptions took place was so irregular that some hundreds of feet of lava must have accumulated before the higher chalk hills were buried under the volcanic discharges. But it seems to me that much of this inequality in the height of the upper surface of the Chalk is to be attributed to unequal movements since the volcanic period, which involved the basalt in their effects, as well as the platform of Chalk below it. Had the present undulations of that platform been older than the volcanic discharges, it is obvious that upper portions of the basalt-series would have overlapped lower, and would have come to rest directly on the Chalk. But this arrangement, so far as I am aware, never occurs, except on a trifling scale. Wherever the Chalk appears, it is covered by sheets of the lower and not of the upper of the two groups into which the Antrim basalts are divisible. We have actual proof of considerable terrestrial disturbance, subsequent to the date of the formation of the volcanic plateau. Thus, near Ballycastle, a fault lets down the basalt and its Chalk platform against the crystalline schists of that district. On the east side of the fault, the Chalk is found far up the slope, and circling round the base of the beautiful cone of Knocklayd—an outlier of the basalt which reaches a height of 1695 feet. The amount of vertical displacement of the volcanic sheets is here 700 feet.* Many other displacements, as shown by the mapping of my colleagues in the Geological Survey, have shifted the base of the escarpment from a few inches up to several hundred feet.

It is evident, therefore, that the present position of the Chalk platform is far from agreeing with that which it presented to the outflow of the sheets of basalt. But, on the other hand, there can be no doubt that its surface at the beginning of th evolcanic outbursts was not a level plain. It was probably a rolling country of low bare chalk-downs, like parts of the south-east of England. The Chalk attains its maximum thickness of perhaps 250 feet at Ballintoy. But it is liable to rapid diminution. On the shore at Ballycastle, about 150 feet of it can be seen, its base being concealed ; but only 2½ miles to the south, on the outlier of Knocklayd, the thickness is not quite half so much. On the west side of the plateau also, there are rapid changes in the thickness of Chalk. Such variations appear to be mainly attributable to unequal erosion before the outflow of the basalts. So great indeed had been the denudation of the Cretaceous and underlying Secondary formations previous to the beginning of the volcanic outbursts, that in some places the whole of these strata had been stripped off the country, so that the older platform of Palæozoic or still more ancient masses was laid bare. Thus, on the west side of the escarpment, the basalt steals across the Chalk and comes to rest directly upon Lower Carboniferous rocks.

The authors who have described the junction of the Chalk and basalt in Antrim have generally referred to the uneven surface of the former rock as exposed in any given section. The floor on which the basalt lies is remarkably irregular, rising into ridges and sinking into hollows or trenches, but almost everywhere presenting a layer of earthy rubbish made of brown ferruginous clays, mixed with pieces of flint, chalk, and even basalt.† The flints are generally reddened and shattery. The chalk itself has been described as indurated, and its flints as partially burnt by the influence of the overlying basalt. But I have not noticed, at any locality, evidence of alteration of the solid chalk, except where dykes or intrusive sheets have penetrated it.‡ There can be no doubt that the hardness of the rock is an original peculiarity, due to the circumstances of its formation. The irregular earthy rubble, that almost always intervenes between the chalk and the base of the basalt, like the "clay with flints" so general over the Chalk of southern England, no

* Explanatory Memoir of Sheets 7 and 8, *Geological Survey, Ireland*, by Messrs SYMES, EGAN, and M'HENRY (1888), p. 37.

† PORTLOCK, Report on Geology of Londonderry, &c. (*Geological Survey*), p. 117.

‡ See PORTLOCK, *op. cit.*, p. 116.

doubt represents long-continued subærial weathering previous to the outflow of the basalt. Even, therefore, if there were no other evidence, we might infer with some confidence from this layer of rubble, that the surface over which the lavas were poured was a terrestrial one.

The Antrim plateau is not only the largest in the British Islands, it is also the most continuous and regular. It may be regarded, indeed, as one unbroken sheet of volcanic material, with no such mountainous masses of eruptive rock as in the other plateaux disturb the continuity of the horizontal or gently inclined sheets of basalt. Around its margin, indeed, a few outliers tower above the plains, and serve as impressive memorials of its losses by denudation. Of these, by much the most picturesque and imposing, though not the loftiest, is Knocklayd already referred to, which forms so striking a feature in the north-east of Antrim.

The total thickness of volcanic rocks in the Antrim plateau exceeds 1000 feet; but, as the upper part of the series has been removed by denudation, the whole depth of lava originally poured out cannot now be told. A well-marked group of tuffs and clays, traceable throughout a large part of Antrim, forms a good horizon in the midst of the basalts, which are thus divisible into a lower and upper group.

The Lower Basalts have a thickness of from 400 to 500 feet. But, as already mentioned (p. 80), they rapidly die out in about six miles to no more than 40 feet at Ballintoy. They are distinguished by their general cellular and amygdaloidal character, and less frequently columnar structure. The successive flows, each averaging perhaps about 15 feet in thickness, are often separated by thin red ferruginous clayey partings, sometimes by bands of green or brown fine gravelly tuff. The most extensive sheet of tuff is one which occurs in the lower part of the group at Ballintoy, and can be traced along the coast for about five miles. In the middle of its course, near the picturesque Carrick-a-raide, it reaches a maximum thickness of about 100 feet, and gradually dies out to east and west. The neck of coarse agglomerate at Carrick-a-raide, already referred to, is doubtless the vent from which this mass of tuff was discharged (see fig. 29). Owing to the thinning out of the sheets of basalt, as they approach the vent, the tuff comes to rest directly on the Chalk, and for some distance westwards forms the actual base of the volcanic series.* Occasional seams of carbonaceous clays, or even of lignite, appear on different horizons. Beneath the whole mass of basalt, indeed, remains of terrestrial vegetation here and there occur. Thus, near Banbridge, county Down, a patch of lignite, 4 feet 10 inches thick, underlies the basalt, and rests directly on Silurian rocks. Such fragmentary records are an interesting memorial of the wooded land-surface over which the earliest outflows of basalt spread.

The central zone of tuffs, clays, and iron-ore is generally from 30 to 40 and sometimes as much as 70 feet thick. From the occurrence of the ore in it, this zone has been explored more diligently in recent years than any other group of rocks in Antrim, and its outcrop is now known over most of the district in which it occurs. The iron-ore bed

* See Explanation of Sheets 7 and 8 of the *Geological Survey of Ireland* (1888), p. 23.

varies from less than an inch up to 18 inches in thickness, and consists of pisolitic concretions of hæmatite, from the size of a pea to that of a hazel nut, wrapped up in a soft ochreous clayey matrix. Where it is absent, its place is sometimes taken by an aluminous clay, worked as "beauxite," which has yielded stumps of trees and numerous leaves and cones. Beneath the iron-ore, or its representative, lies what is called the "pavement,"—a ferruginous tuff, 8 to 10 feet thick, resting on "lithomarge,"—a lilac or violet mottled aluminous earth sometimes full of rounded blocks or bombs of basalt. The well-known horizon for fossil plants at Ballypallidy is a red tuff in this zone.

This intercalated band of ferruginous deposits forms one of the most persistent and interesting features in the Antrim plateau. The actual area now occupied by it has been so reduced by denudation into mere scattered patches that it probably does not exceed 170 square miles. But the zone can be traced from Divis Hill, near Belfast, to Rathlin Island, a distance of 50 miles, and from the valley of the Bann to the coast above Glenarm, more than 20 miles. There can be little doubt that it was once continuous over all that area, and that it probably extended some way further on all sides. Hence, the original area over which the iron-ore and its accompanying tuffs and clays were laid down can hardly have been less than 1000 square miles. This extensive tract was evidently the site of a lake during the volcanic period, formed by a subsidence of the floor of lower basalts. The salts of iron contained in solution in the water, whether derived from the decay of the surrounding lavas or from the discharges of chalybeate springs, were precipitated as peroxide in pisolitic form, as similar ores are now being formed on lake-bottoms in Sweden. For a long interval, quiet sedimentation went on in this lake, the only sign of volcanic energy during that time being the dust and stones that were thrown out and fell over the water-basin, or were washed into it by rains from the slopes around.

Immediately above the iron-ore, or separated from it in places by only a few inches of tuff, comes the group of Upper Basalts, which varies up to 600 feet in thickness, though, as the upper portion has been everywhere removed by denudation, no measure remains of what may have been the original depth of the group. The general character of these basalts is more frequently columnar, black and compact, and with fewer examples of the strongly amygdaloidal structure so conspicuous in the lower group. But this distinction is less marked in the south than in the north of Antrim, so that where the intervening zone of tuffs and iron-ore disappears, no satisfactory line of division can be traced between the two groups of basalt. The occurrence of that zone, however, by giving rise to a hollow or slope, from which the upper basalts rise as a steep bank or cliff, furnishes a convenient topographical feature for mapping the boundary of these rocks. Among the upper basalts, also, there is perhaps a less frequent occurrence of those thin red partings of bole between the successive flows, so conspicuous in the lower group. But the flows are not less distinctly marked off from each other. Nowhere can their characteristic features be better seen than along the magnificent range of cliffs from the Giant's Causeway eastwards. The columnar bed that forms the Causeway is the lowest sheet of the upper group, and may be seen resting directly on the zone of grey and red tuffs. It is about 60 or 70 feet thick; and, while perfectly regular in its columnar structure at the Causeway and the "Organ," assumes further eastward the confusedly starch-like arrangement of prisms already referred to. But, in the great cliff section of the "Amphitheatre," the more regular structure is resumed, the bed swells out to about 80 feet in thickness, and columns of that length run up the face of the precipice, weathering out at the top into separate pillars, which, perched on the crest of an outstanding ridge, are known as the "Chimneys." The basalt-beds that succeed the lowest one are each only about 15 to 20 feet thick.

Between the successive sheets of the upper basalts thin seams of red ferruginous clay, though, as I have said, less frequent perhaps than in the lower group, continue to show that the intervals between successive eruptions were of sufficient duration to admit of considerable subærial decay of the surface of a lava before the outflow of the next bed. Occasional thin layers of tuff also, and even of pisolitic iron-ore, have been observed among these higher basalts. But the most interesting and important intercalations are inconstant seams of lignite. One of the most conspicuous of these lies immediately above the basalt of the "Causeway," where it was long worked for fuel, and was found to be more than 6 feet thick. But it is quite local, as may be seen at the "Organ" over which it lies, with a thickness of only 12 inches, rapidly dying out so as to allow the basalts above and below it to come together. The removal of the upper portion of the basalts prevents us from carrying the volcanic history of the Irish plateau further.

It is obvious that nowhere in Antrim does any trace exist of a central vent or cone from which the volcanic materials were discharged. There is no perceptible thickening of the individual basalt sheets, nor of the whole series in one general direction, in such a manner as to point to the site of some chief focus of eruption. Nor can we place reliance on the inclination of the several parts of the plateau. I have pointed out that the varying dip of the beds must be attributed mainly to post-volcanic movements, or at least to movements which, if not later than all the phases of volcanic action, must have succeeded the outpouring of the plateau-basalts. There has been a general subsidence towards the central and southern portions of the plateau, and this movement has no doubt given rise to the hollow that is now occupied by Lough Neagh. But nowhere in the depression is there any trace of the ruins of a central cone or focus of discharge.

The Antrim plateau, in these respects, resembles the others. But it differs from them in one important particular. It has nowhere been disrupted by huge eruptive bosses of younger rocks, such as have broken up the continuity of the old lava-fields further north. Yet it is not without its memorials also of these younger protrusions. It has some feeble representatives of the great acid bosses of the Inner Hebrides, and it contains not a few excellent examples of true volcanic vents. To these fuller reference will be made in later pages.

2. *Mull.*—This plateau, besides the island of Mull, embraces a portion of Morven,

and, stretching across Loch Sunart, includes the western part of the peninsula of Ardnamurchan. That it formerly extended far beyond its present limits is impressively indicated by its margin of cliffs and fringe of scattered islands and outliers. It went west, at least, as far as the Treshnish Isles, which are composed of basalt. On its eastern border, a capping of basalt on the top of Ben Iadain (1873 feet) in Morven, and others further north, prove that its volcanic sheets once spread far into the interior of Argyleshire (fig. 20). On the south, its fine range of lofty cliffs, with their horizontal bars of basalt, bear witness to the diminution which it has undergone on that side ; while, on the north, similar sea-walls tell the same tale. Not only has it suffered by waste along its margin, it has also been deeply trenched by the excavation of glens and arms of the sea. The Sound of Mull cuts it in two, and the mainland portion is further bisected by Loch Sunart, and again by Loch Aline. The island of Mull is so penetrated by sea-lochs that a comparatively slight depression would turn it into a group of islands. But, besides its enormous denudation, the Mull plateau has been subjected to great disruption from

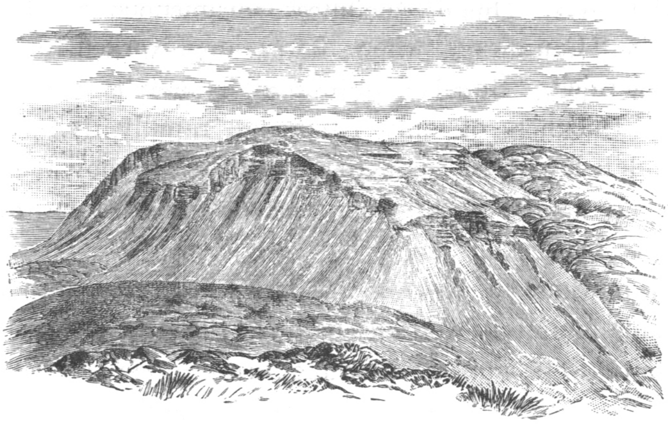


FIG. 20.—Basalt-Capping on top of Ben Iadain, Morven.

subterranean movements. In the southern portion of the island, it has been broken up by the intrusion of large bosses and sheets of gabbro, and by masses as well as innumerable veins of various granitoid and felsitic rocks. In Ardnamurchan, it has suffered so much disturbance from the same cause that its original structure has been almost obliterated over a considerable area. Moreover, it has been dislocated by many faults, by which different portions have been greatly shifted in level. The most important of these breaks is one noticed by Professor JUDD, and visible to every tourist who sails up the Sound of Mull. It traverses the cliffs on the Morven side, opposite Craignure, bringing the basalts against the crystalline schists, and strikes thence inland, wheeling round into the long valley in which Lochs Arienas and Teacus lie. On its western side, the base of the basalt-series is almost at the sea-level ; on its eastern side, that platform rises high into the outliers of Beinn na h-Uamha (1521 feet) and Beinn Iadain. The amount of displacement here is probably not much less than 1500 feet. Many other minor faults in the same district show how much the crust of the earth has been fractured here since older Tertiary time.*

Nevertheless, in spite of the extent to which the Mull plateau has suffered from denudation and subterranean disturbance, and indeed in consequence thereof, this plateau presents clear sections of many features in the history of the basalt-outflows and of the subsequent phases of Tertiary volcanic action which cannot be seen in the more regular and continuous tableland of Antrim. Moreover, it still possesses in its highest mountain, Ben More (3169 feet), a greater thickness and a higher series of lavas than can now be seen in any other of the plateaux.

It will be readily understood that, in the case of this plateau, the difficulties already referred to in regard to that of Antrim, of tracing the probable form of ground on which the volcanic eruptions began, are considerably increased. We can dimly perceive that the depression in the crystalline rocks of the Highlands which had, from at least the older part of the Jurassic period, stretched in a N.N.W. direction along what is now the western margin of Argyleshire, lay beneath the sea in Jurassic time, and was then more or less filled up with sedimentary deposits. The hollow appears thereafter to have become a land-valley, whence much of the Jurassic strata was cleared out by denudation before its subsequent submergence under the sea in which the upper Cretaceous deposits accumulated. Professor JUDD has shown how relics of these Cretaceous strata appear on both sides of the plateau from under the protecting cover of basalt-sheets. But, before the volcanic eruptions began, the area had once again been raised into land, and the youngest Secondary formations had been extensively eroded.

In their general aspect the basalts of Mull agree with those of Antrim, and the circumstances under which they were erupted were no doubt essentially the same. But considerable differences in detail are observable between the succession of rocks in the two areas. The total depth of basalt-sheets in Mull is greater than in any other of the plateaux. When I first visited the island in 1866, the only available maps, with any pretensions to accuracy, were the Admiralty charts; but, as these do not give the interior except in a generalised way, it was difficult to plot sections from them, and to arrive at satisfactory conclusions as to the thickness of different groups of rock. Accordingly, as the successive nearly flat flows of basalt can be traced from the sea-level up to the top of Ben More, I contented myself with the fact that the total depth of lava-beds in Mull was at least equal to the height of that mountain, or 3169 feet. The publication of the Ordnance Survey Maps now enables us to make a nearer approximation to the truth. From the western base of the magnificent headland of Gribon, the basalts in almost horizontal beds rise in one vast sweep of precipice and terraced slope to a height of over 1600 feet, and then stretch eastwards to pass under the higher part of Ben More, at a distance of some 8 miles. They have a slight easterly inclination, so that the basement

* There are no fewer than three faults in the basalt-capping on the summit of Ben Iadain. By bringing the basalts and schists into juxtaposition, they have given rise to topographical features that can be seen even from a distance. See fig. 20.

beds seen at the sea-level, at the mouth of Loch Scridain, gradually sink below that level as they go eastward. It is not easy to get a measurement of dip among these basalts, except from a distance. If we take the inclination at only 1°, the beds which are at the base of the cliff on the west, must be about 700 feet below the sea on the line of Ben More, which would give a total thickness of nearly 3900 feet of bedded lava below the top of that mountain. We shall not probably overestimate the thickness of the Mull plateau if we put it at 3500 feet.

The base of the volcanic series of Mull can best be seen on the south coast at Carsaig, and at the foot of the precipices of Gribon. As already stated, it is there found resting above Cretaceous and Jurassic rocks. The lowest beds are basalt-tuffs, of the usual dull-green colour. They are in places much intermingled with sandy and gravelly sediment, as if the volcanic débris had fallen into water where such sediment was in course of deposition. One of the most interesting features, indeed, in this basement part of the series, is the occurrence of bands of non-volcanic material which accumulated after the tuffs and some of the lavas had been erupted, but before the main mass of basalts. Those at Carsaig include a lenticular bed, 25 feet thick, of rolled flints, which, with some associated sandy bands, lies between sheets of basalt. On the opposite side of the promontory is the well-known locality of Ardtun, from which the first land-plants in the volcanic series were determined. The actual base of the basalts is not there seen, being covered by the sea. The "leaf-beds," with their accompanying sandstones, gravels, and limestone, lie upon a sheet of basalt, which in some parts is exceedingly slaggy on the top, passing down into a black compact basalt, and assuming at the base of the cliff a columnar arrangement, with the prisms curved and built up endways towards each other. Some of the gravels exceed 30 feet in thickness, and consist of rolled flints, bits of chalk, and pieces of basalt, and of other basic igneous rocks. But some of their most interesting ingredients are pebbles of sanidine lavas, which have been recognised in them by Mr G. COLE.* No known protrusions of such lavas occur anywhere beneath or interstratified with the plateau-basalts. As will be afterwards shown, all the visible acid rocks, the geological relations of which can be ascertained, are of younger date than these basalts. I am disposed to regard the fragments found in the Ardtun conglomerates as probably derived from some of the basalt-conglomerates of the plateau, in which fragments of siliceous igneous rocks do occur. Though there is no evidence that any lavas of that nature were poured out at the surface before or during the emission of the basalts, the contents of these fragmental volcanic accumulations prove that such lavas, already consolidated, lay at some depth beneath the surface, and that fragments were torn off from them during the explosions that threw out the materials of the basalt-conglomerates to the surface.

Mr STARKIE GARDNER has called attention to the extraordinarily fresh condition of the vegetation in some of the layers of the Ardtun section. One of the leaf-beds he has found to be made up for an inch or two of a pressed mass of leaves, lying layer upon

* *Quart. Jour. Geol. Soc.*, xliii. (1887) p. 277.

layer, and retaining almost the colours of dead vegetation. Among the plants represented is a large purple *Ginkgo* and a fine *Platanites*, one leaf measuring 15½ inches long by 10½ broad. The characteristic dicotyledonous leaves at this locality possessed relatively large foliage.*

To the early observations of MACCULLOCH we are indebted for the record of an interesting fact in connection with the vegetation of the land-surface over which the first lava-flows spread. He figured a vertical tree trunk, imbedded in prismatic basalt, and rightly referred it to some species of fir.† This relic may still be seen under the basalt-precipices of Gribon. Mr GARDNER found it to be "a large trunk of a coniferous tree, five feet in diameter, perhaps *Podocarpus*, which has been enveloped, as it stood, in one of the flows of trap to the height of 40 feet. Its solidity and girth evidently enabled it to resist the fire, but it had decayed before the next flow passed over it, for its trunk is a hollow cylinder filled with débris, and lined with the charred wood. A limb of another, or perhaps the same tree, is in a fissure not far off." ‡

At different levels in the volcanic series of Mull, beds of lignite and even true coal are observable. These seem to be always mere lenticular patches, only a few square yards in extent. The best example I have met with is among the basalts near Carsaig. It is in part a black glossy coal, and partly dull and shaly. Some years ago it was between two and three feet thick, but now, owing to its having been dug away by the shepherds, only some six or eight inches are to be seen. It lies between two basalt-flows, and rapidly disappears on either side.

More frequent than these inconstant layers of fossil vegetation are the thin partings of tuff and layers of red clay, sometimes containing iron-ore, which occur at intervals throughout the series between different flows of basalt. But even such intercalations are of trifling thickness, and only of limited extent. The magnificent precipices of M'Gorry's Head and Gribon expose a succession of beds of columnar amorphous and amygdaloidal basalt, which must attain a thickness of at least 2500 feet, before they are overlain by the higher group of lavas in Ben More. On the east side of the island, thin tuffs and bands of basalt-conglomerate occur on different horizons among the bedded basalts, from near the sea-level up to the summit of the ridge which culminates in Beinn Meadhon (2087 feet), Dun-da-Ghaoithe (2512 feet), and Mainnir-nam-Fiadh (2483 feet).

Above the ordinary compact and amygdaloidal basalt comes the higher pale group already referred to as forming the uppermost part of Ben More, whence it stretches continuously along the pointed ridge of A'Chioch, and thence northwards into Beinn Fhada. The same felspathic lavas are likewise found in two outliers, capping Beinn a' Chraig, a mile further north, and I have found fragments of them on some of the loftier ridges to the south-east. This highest and youngest group of lavas in the plateaux has been reduced to mere isolated patches, and a little further denudation will remove it

* For fuller local details regarding the Ardtun leaf-beds, I may refer to the original paper by the DUKE OF ARGYLL (*Quart. Jour. Geol. Soc.*, vii. p. 89), and to the recent memoir by Mr STARKIE-GARDNER (*op. cit.*, xliii., 1887, p. 270).

† *Western Islands*, vol. i. p. 568, and plate xxi. fig. 1.

‡ *Quart. Jour. Geol. Soc.*, xliii. p. 283.

altogether. Yet it is not less than about 800 feet thick, and consists of bedded lavas, which alternate with and follow continuously and conformably upon the top of the ordinary plateau-basalts. I have described these rocks as dull, finely crystalline or compact, light-grey in colour, and weathering with a characteristic platy form, which has been mistaken for the bedding of tuffs. The fissility, however, has none of the regularity or parallelism of true bedding, and may be observed to run sometimes parallel with the bedding of the sheets, sometimes obliquely or even at right angles to it. Even where this structure is best developed, the truly crystalline nature of the rocks can readily be detected. Some of them are porphyritic and amygdaloidal, the very topmost bed of the mountain being a coarse amygdaloid. Intercalated with these curious rocks there are others in which the ordinary characters of the dolerites and basalts of the plateaux can be recognised. The amygdaloids are often full of delicate prisms of epidote.

In Mull, as in the other areas of terraced basalts, we everywhere meet with gently inclined sheets, which do not thicken out individually or collectively in any given direction, except as the result of unequal denudation. So far as I have been able to discover, they afford no evidence of any great volcanic cone from which they proceeded. Their present inclinations are unquestionably due, as in Ireland, to movements subsequent to the formation of the plateau. In Loch-na-keal they dip gently to the E.N.E.; in Ulva and the north-west coast to N.N.E.; near Salen to W.S.W. on the one side, and N.W. on the other. Round the southern and eastern margins of the mountainous tract of the island, they dip generally inwards to the high grounds.

The Mull plateau presents a striking contrast to that of Antrim, in the extraordinary extent to which it has been disrupted by later protrusions of massive basic and acid rocks over a rudely circular area, extending from the head of Loch Scridain to the Sound of Mull, and from Loch-na-keal to Loch Buy. The bedded basalts have been invaded by masses of dolerite, gabbro, and granophyre, with various allied kinds of rock. They have not only been disturbed in their continuity, but have undergone considerable metamorphism.

Again, further to the north, in the promontory of Ardnamurchan, the plateau has been disrupted in a similar way, and only a few recognisable fragments of it have been left. These changes will be more appropriately discussed in connection with similar phenomena in the other plateaux further north.

3. *Small Isles.*—This plateau, the smallest and most discontinuous of the four, includes the islands of Eigg, Rum, Canna, and Muck, which form the parish of Small Isles. That the fragments of the bedded volcanic masses, preserved on each of these islands, were once connected can hardly be doubted. Indeed, as already stated, they were not improbably united with the plateau of Skye on the north, and with that of Ardnamurchan and Mull on the south. Taking the whole space of land and sea within which the basalt of Small Isles is now confined, we may compute it at not much less than 200 square miles. In Eigg, Muck, and Canna, the basalts retain their almost horizontal position, and from underneath them emerge the Jurassic strata on which they lie. The

central part of the plateau, forming the island of Rum, is, however, much less regular. Four small outliers of the basalts lie at levels of 1200 feet and upwards, on the western slope of that island. They are underlain by a thick mass of red (Cambrian or Torridon) sandstones, which form the northern half of the island, and which southwards are connected with a confused series of gneisses and schists. These rocks are doubtless a continuation of the red sandstones and schists of Sleat, in Skye, and like them have been subjected to those post-Silurian convolutions and metamorphism whereby Archæan gneisses have been brought above younger rocks, and the whole have been crushed and rolled out so as to assume a new schistose arrangement. Before the time when volcanic action began, a mass of high ground, consisting of these ancient rocks, stood where the island of Rum is now situated. The streams of basalt spread around it, not only covering the surrounding low tracts of Jurassic rocks, but gradually accumulating against the hills, and thus reducing them both in area and in height above the plain.*

The plateau has been obliterated over the centre and south of Rum by the extrusion of enormous masses of gabbro, and some later granitoid rocks. The most extensive of its fragmentary portions is that of Eigg, where the sheets of basalt, resting on Jurassic beds and dipping gently southwards, can be studied all round the island in a continuous range of precipices (see fig. 62).

The general aspect and succession of volcanic sheets in the area of Small Isles agree with those of Antrim and of the older part of the plateau of Mull. The basalts in Eigg, Canna, and Muck rise into ranges of fine sea-walls, sometimes five or six hundred feet high. The thickest mass of them occurs in Eigg, where, lying unconformably upon different platforms of the Jurassic rocks, they attain a thickness of about 1100 feet. They consist of the usual types—black, fine-grained, columnar and amorphous basalts, more coarsely crystalline dolerites, and dull earthy amygdaloids with red partings, and occasional thin bands of basalt-conglomerate or tuff. The individual beds range in thickness from 20 to 50 or 60 feet. Though they seem quite continuous when looked at from the sea, yet, on closer examination, they are found not unfrequently to die out, the place of one bed being taken by another, or even by more than one, in continuation of the same horizon. The only marked petrographical variety which occurs among them is a light-coloured band which stands out conspicuously among the darker ordinary sheets of the escarpment on the east side of the island. The microscopic characters of this rock show it to belong to the same series of highly felspathic lavas as the "pale group" of Ben More, in Mull. It is strongly vesicular, and the cells are in some parts so flattened and elongated as to impart a kind of fissile texture to the bed.†

This plateau has suffered even more than that of Mull from the combined influence

* That the lava-fields did not completely bury this nucleus of older rock has been supposed to be shown by the fragments of red sandstone found in the ancient river-bed of Eigg, which was scooped out of the basalt-plateau and sealed up under pitchstone. But I am disposed to think that these fragments, together with those of Jurassic sandstone, came, not from Rum, but from some district more to the north and east, as will be adverted to in a later part of this paper.

† For further details regarding this plateau in Eigg, see my paper, *Quart. Jour. Geol. Soc.* xxvii. (1871) p. 290.

of later intrusive bosses and of prolonged denudation. That it once extended over the site of the whole of Rum can hardly be doubted. The edges of the beds that form the outliers would, if prolonged, cover the northern or lower half of the island, where the ancient Palæozoic and Archæan rocks form the surface. In the southern half, the continuity of the basalts has been partly obscured and partly destroyed by the protrusion of the great masses of gabbro that form the singularly picturesque mountain group to which this island owes its prominence as a land-mark far and wide along the west coast of Scotland.

4. *Skye.*—This is the largest and geologically most important of all the Scottish plateaux. Comprising the island of Skye, at least as far south as Loch Eishort, the west side of Scalpa and the southern half of Raasay, and probably extending to the Shiant Isles, it may be reckoned to embrace an area of not less than 800 square miles. The evidence that its limits are now greatly less than they originally were is, like that of Mull, abundant and impressive. Its truncated edges, rising here and there for a thousand feet as a great sea-wall above the breakers at their base, and presenting everywhere their succession of level or gently inclined bars of basalt-beds, are among the most stupendous

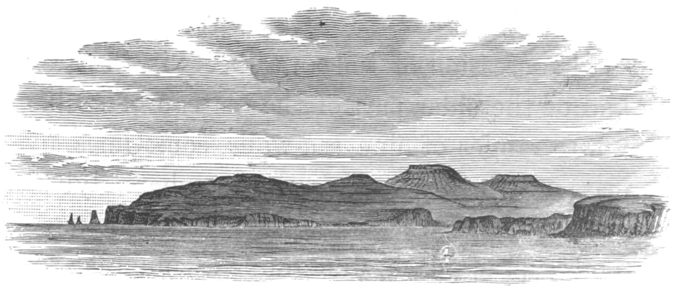


Fig. 21.—Terraced Hills of Basalt Plateau (Macleod's Tables), Skye.

monuments of denudation in this country. But still more striking to the geologist is the proof, furnished along the eastern margin of the plateau, that the Jurassic and other older rocks there visible were originally buried deep under the basalt-sheets, which have thus been entirely stripped off that part of the country.

Throughout most of the district, wherever the base of the basalts can be seen, it is found to rest upon some member of the Jurassic series, but with a complete unconformability. The underlying sedimentary strata had been dislocated and extensively denuded before the volcanic period began. On the southern margin, however, the red (Cambrian or Torridon) sandstones emerge from under the basalts of Loch Scavaig, and extending into the island of Soay are no doubt prolonged under the sea into Rum. This ridge probably represents the range of the ancient high ground of the latter island already referred to.

Nowhere are the distinctive topographical features and geological structure of the basalt-plateaux more impressively displayed than in the northern half of the island of Skye. The green terraced slopes, with their parallel bands of brown rock formed by the outcrop of the nearly flat basalt-beds, rise from the bottoms of the valleys into flat-topped ridges and truncated cones (fig. 21). The hills everywhere present a curiously tabular form that bears witness to the horizontal sheets of rock of which they are composed.* And along the stupendous sea-precipices, each successive sheet of basalt can be counted from base to summit, and followed from promontory to promontory (fig. 22). In the district of Trotternish, the basalt hills reach a height of 2360 feet. Further west, the singular flat-topped eminences, called "Macleod's Tables" (fig. 21), ascend to 1600 feet.

Along the western side of Skye, the basalts descend beneath the level of the Atlantic. Along the eastern side their base runs on the top of the great Jurassic escarpment, whose white and yellow sandstones form there, and on the east side of Raasay, so prominent a feature in the landscape. To the south-east, the regularity of the volcanic plateau is effaced, as in Mull and Ardnamurchan, by the protrusion of the extensive mass of eruptive rocks constituting the Cuillin and Red Hills, east of which the basalts have been almost

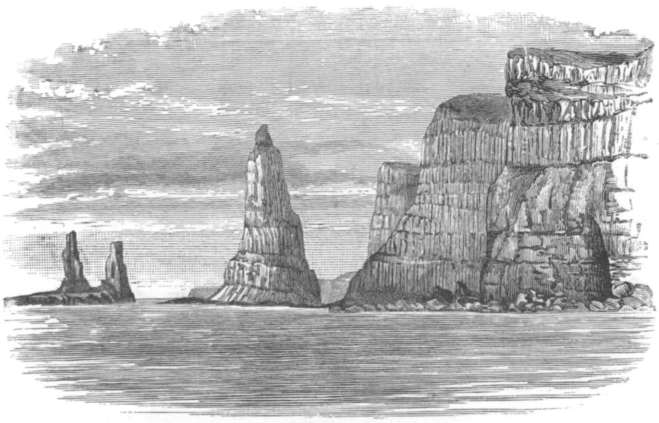


FIG. 22.—"Macleod's Maidens" and part of Basalt Cliffs of Skye.

entirely removed by denudation, so as to expose the older rocks which they once covered, and through which the later eruptive bosses made their way. This is undoubtedly the most instructive district for the study of that later phase in the volcanic history of Britain comprised in the eruptive bosses of basic and acid rocks.

The magnificent plateau of this island has been so profoundly cut down into glens and arms of the sea, and its component layers are exposed along so many leagues of noble precipice, that its structure is perhaps more completely laid open than that of any of the other areas. It is built up of a succession of basalts and dolerites of the usual types, which probably reach a thickness of more than 2000 feet, though in their instance, also, denudation has left only a portion of them, without any evidence by which to reckon what their total original depth may have been. In rambling over Skye, the geologist is more than ever struck with the remarkable scarcity and insignificance of the interstratifications of tuff or of any other kind of sedimentary deposit between the successive lava-

* These features are more fully described in my *Scenery of Scotland*, 2d edit. (1887), pp. 74, 145, 216.

sheets. In many places, indeed, bands of dirty-green tuff or basalt-conglomerate may be observed, sometimes, as at Portree harbour, associated with lenticular seams of coal, from a few inches to three feet in thickness. Sheets of finer tuff of brighter colours, violet, bluish, and red, like those of Antrim, form conspicuous features in some of the western sea-cliffs, as at Talisker. But compared with the enormous area and thickness of the basalts, these fragmentary ejections are of the most trifling extent.

In no part of the Tertiary volcanic area of Britain can the characters of the lavas and the structure of the plateaux be so impressively seen as along the west side of Skye, north of Loch Bracadale. The precipices rise sheer out of the sea, to heights of sometimes 1000 feet, and from base to summit every individual bed may be counted. As an illustration of the general succession of beds, I give here a diagrammatic view of the

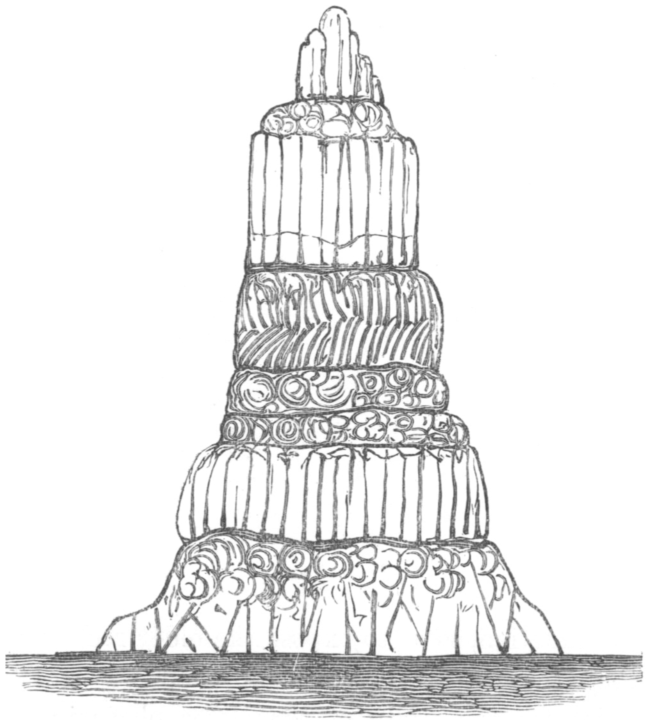


FIG. 23.—Section of the largest of Macleod's Maidens.

largest of M'Leod's Maidens—the three wierd sea-stacks that rise so grandly in front of the storm-swept precipice at the mouth of Loch Bracadale. The height of the stack must be at least 150 feet (figs. 22 and 23). About ten distinct sheets of igneous rock can be counted in it, which gives an average thickness of 15 feet for the individual beds. It will be observed that there is a kind of alternation between the compact, prismatic basalts and the more earthy amygdaloids, but that the former are generally thickest.* These features,

* A striking and illustrative contrast between the relative thickness of the beds of the two kinds of rock is supplied by the fine sections of this district. The amygdaloids range from perhaps 6 or 8 to 25 or 30 feet; but the prismatic basalts, while never so thin as the others, sometimes enormously exceed them in bulk. In the island of Wiay, for example, a bed of compact black basalt, with the confused starch-like grouping of columns, reaches a thickness of no less than 170 feet. Its bottom rests upon a red parting on the top of a dull greenish earthy amygdaloid.

which are repeated on cliff after cliff, may be considered typical for all the plateaux. Another characteristic point, well displayed here, is the intervening red parting between the successive beds. If the occurrence and thickness of this layer could be assumed as an indication of the relative lapse of time between the different flows of lava, it would furnish us with a rude kind of chronometer for estimating the proportionate duration of the intervals between the eruptions. It is to be noticed on the top both of the compact prismatic and of the earthy amygdaloidal sheets; but is more frequent and generally thicker on the latter than on the former, which may only mean that the surfaces of the cellular lavas were more prone to subærial decay than those of the compact varieties. Nevertheless, I am disposed to attach some value to it, as an index of time. In the present instance, for example, it seems to me probable that the lavas in the lower half of M'Leod's Maiden, where the red layers are very prominent, were poured out at longer intervals than those that form the upper half.

Another characteristic plateau-feature is admirably displayed in Skye—the flatness of the basalts and the continuity of their level terraces (though not of individual sheets) from cliff to cliff and hill-side to hill-side. This feature may be followed with almost tiresome monotony over the whole of the island, north of a line drawn from Loch Brittle to Loch Sligachan. Throughout that wide region, the regularity of the basalt-plateau is unbroken, except by minor protrusions of eruptive rock, which, so far as I have noticed, do not seriously affect the topography. But south of the line just indicated, the plateau undergoes the same remarkable change as in Rum, Ardnamurchan, and Mull. Portions of it which have survived indicate with sufficient clearness that it once spread southwards and eastwards over the mountainous district, and even farther south into the low parts of the island. Its removal from that tract has been of the utmost value to geological research, for some of the subterranean aspects of volcanism have thereby been revealed, which would otherwise have remained buried under the thick cover of basalt. Denudation has likewise cut deeply into the eruptive bosses, and has carved out of them the groups of the Red Hills and the Cuillins, to whose picturesque forms Skye owes so much of its charm.

In this, as in each of the other plateaux, there is no trace of any thickening out of the basalts towards a supposed central vent of eruption. The nearly level sheets may be followed up to the very edge of the great mountainous tract of eruptive rocks, retaining all the way their usual characters; they do not become thicker there either collectively or individually, nor are they more abundantly interstratified with tuffs or volcanic conglomerates. On the contrary, their very base is exposed around the mountain ground, and the thickest interstratifications of fragmentary materials are found at a distance from that area. So far as regards the structure of the remaining part of the plateau, the eruption of the gabbros and granitoid rocks might apparently have taken place as well anywhere further north.

§ 3. Vents of Eruption.

In the approximate horizontality and regularly stratified arrangement of their component beds of lava, the plateaux of Britain resemble those of older Tertiary and still earlier date in other volcanic tracts, both in the Old and the New World, where the absence of any obvious vents from which the molten material flowed long presented a difficulty to geological students. I have stated that in no one instance have I been able to discover a trace of any central volcano, whence the sheets of basalt in the British plateaux could have proceeded. On the contrary, the uniformity of the beds in petrographical character, thickness, and persistent flatness point, I think, unmistakably to the occurrence not of a few great volcanoes, but of many minor vents breaking out one after another and shifting from district to district. Only by some such distribution of the foci of discharge can we account for the continuity and horizontality of the basalts that have gradually built up the plateaux. It is one of the most interesting points in this volcanic history that, in spite of the enormous geological revolutions that have passed since they became extinct, the sites of many scattered vents can still be recognised. A far greater number must lie buried under the basalts, and of others the positions are concealed by the sea, which now covers so large an area of the old lava-fields. Nevertheless, partly on the surface of the plateaux, but still more on the surrounding tracts from which the basalts have been removed by denudation, the stumps of unmistakable vents of discharge stand out prominently amid the general wreck.

Obviously it may be difficult to connect these vents directly with the plateau-lavas. On the one hand, those which project from the surface of the plateaux must, of course, be younger than the basalts through which they rise; how much younger we cannot tell. They may possibly be later than any of the plateau-sheets; they may even belong to a subsequent and waning condition of volcanic action. On the other hand, the vents which can now be traced outside of the present limits of the edges of the plateaux may, like those just mentioned, be younger than the basalt-sheets, or, on the contrary, they may be records of a period of eruptivity anterior to the emission of any of the rocks of the plateaux, and may have been deeply buried under a mass of basalt-beds subsequently removed. Positive demonstration is, from the nature of the case, impossible, unless we could find at the foot of the basalt-escarpment a volcanic vent immediately connected with some of the beds of the plateau above it.* When, however, we reflect that the vents which exist are precisely such as the structure of the plateaux would have led us to expect, we may not unreasonably look on them as part of the phenomena of this section of the volcanic period. Besides, in some cases, their connection with the rocks of the plateaux is as nearly proved as many facts in geology which nobody would now dispute.

The most convenient classification of these vents is according to the nature of the

* The instance of Carrick-a-raide, to be immediately referred to, is as near such a positive demonstration as could be looked for.

material that now fills them. They are either occupied by (*a*) some form of crystalline eruptive rock, or by (*b*) volcanic agglomerate.

(*a*) *Vents filled with Dolerite, Basalt, &c.*—These are by far the most numerous, and as this is what the composition of the plateaux would lead us to anticipate, the fact may be held to confirm the justice of the assumption that these vents were really sources for the plateau-lavas. They are perhaps most conspicuously visible in Antrim, both on the tableland and on the underlying rocks round its edges. The finest example in that district is undoubtedly furnished by the lofty eminence called Slemish, which rises above the surrounding basalt-terraces to a height of 1437 feet above the sea (fig. 24). It is elliptical in ground-plan, measuring some 4000 feet in length by 1000 in breadth. Seen from the north, it appears as a nearly perfect cone. The material of which it consists is a coarsely crystalline olivine-dolerite, presenting under the microscope a nearly holocrystalline aggregate, in which the lath-shaped felspars penetrate the augite, with abundant fresh olivine, and wedge-shaped patches of interstitial matter. The rock is

FIG. 24.—Slemish, a Volcanic Neck or Vent on the Antrim Plateau, seen from the north.

massive and amorphous, except that it is divided by parallel joints into large quadrangular blocks like a granitic rock, and wholly different from the character of the surrounding basalts. The latter, which possess the ordinary characters of the rocks of the plateaux, can be followed to within 80 yards of this neck, which rises steeply from them, but their actual junction with it can nowhere be seen, owing to the depth of talus. At the nearest point to which the two rocks are traceable, the basalts appear somewhat indurated, break with a peculiar splintery fracture, and weather with a white crust. These characters are still better shown on abundant fragments which may be picked up among the débris further up the slope. There can be no doubt, I think, that a ring of flinty basalt, differing considerably in texture from the usual aspect of that rock in the district, surrounds the neck. The meaning of this ring will be more clearly seen from the description of another example in Mull. About four miles to the north-east of Slemish, a smaller and less conspicuous neck rises out of the plateau-basalts. The rock of which it consists is less coarsely crystalline than that of Slemish, but its relations to the surrounding volcanic rocks is obviously the same. On the west side of Belfast Lough a boss of similar rock, about 1200 feet in diameter, rises at the very edge of the basalt escarpment into the eminence known as Carnmony Hill (fig. 25). On its northern side it presents along its wall a mass of interposed volcanic agglomerate.* Of the other doleritic necks scattered over the surface of the Antrim plateau, I will refer to only one which occurs on the hill slopes between Glenarm and Larne. It forms a prominence known as the Scawt Hill, and consists of a boss of basalt, which, in rising through a vent

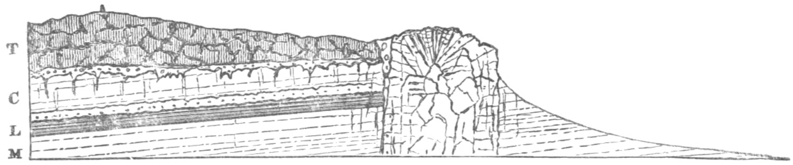


FIG. 25.—Section of Volcanic Vent at Carnmony Hill (E. Hull). T, Lower basalt; C, Cretaceous beds; L, Lower Lias; M, Triassic marls.

in the plateau-sheets, has carried up with it and converted into marble a large mass of chalk which is now exposed along its eastern wall (fig. 26).

As examples of the similar necks which have been exposed by denudation outside the present limits of the plateau, I may allude to those which rise through the Cretaceous and other Secondary strata on the northern coast near Ballintoy. One of the most striking of these may be seen at Bendoo, where a plug of basalt, measuring about 1400 feet in one diameter and 800 feet in another, rises through the Chalk, and alters it around

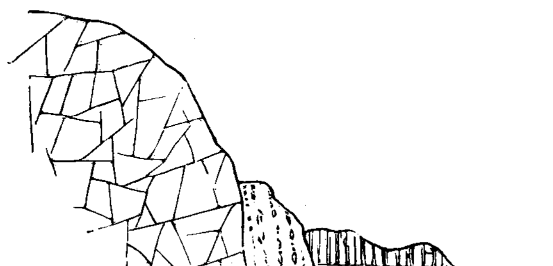


FIG. 26.—Section of the east side of Scawt Hill, near Glenarm. *a*, bedded basalt; *b*, mass of chalk; *c*, basalt neck.

the line of contact (fig. 27). Another remarkably picturesque example is to be seen near Cushendall, where a prominent doleritic cone rises out of the platform of Old Red Sandstone, some distance to the north of the present edge of the volcanic escarpment.

The greater coarseness of grain of the material filling these pipes, compared with that of the sheets in the terraces, is only what the very different conditions of cooling and consolidation would lead us to expect. There is no essential difference of composition

* This neck was recognised by DU NOYER in 1868 as "one of the great pipes or feeders of the basaltic flows." See Prof. Hull, Explanation of Sheets 21, 28, and 29, *Geol. Survey of Ireland* (1876), p. 30.

between the two rocks; but we find that where the erupted material has been poured out at the surface, it has assumed a finely crystalline texture, while, where it has slowly solidified within a volcanic pipe at some depth beneath the surface, and where consequently its component crystals have had more time for development, the resulting structure is much more largely crystalline, with a more complete development of the ophitic structure.

In the island of Mull, another instance of the same kind of vent has been observed and described by Professor JUDD.* It rises in the conspicuous hill, 'S Airde Beinne (Sarta Beinn), about two miles south-west from Tobermory, and consists of a coarsely

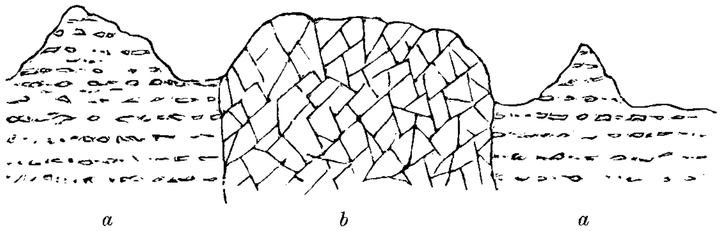


FIG. 27.—Section of Neck of Basalt, Bendoo, Ballintoy. *aa*, Chalk; *b*, Neck.

crystalline dolerite, which becomes rather finer in grain towards the outer margin (fig. 28). No bedding or structure of any kind beyond jointing is perceptible in it. Examined in thin sections under the microscope, this rock is found to be another typical ophitic dolerite, consisting of lath-shaped felspars, embedded in augite masses, with here and there wedge-shaped portions of interstitial matter and grains of olivine. Dr HATCH observes that the felspars contain spherical inclusions of devitrified glass, filled with black granules and trichites and that, under a high power, the interstitial matter is seen to consist mainly of greenish-brown isotropic matter, in which are inclosed small crystals of

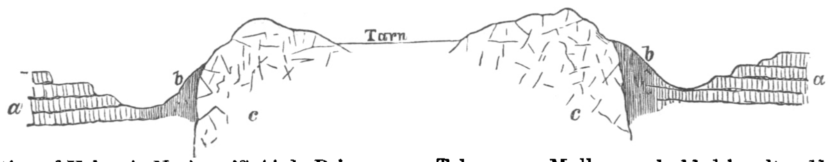


FIG. 28.—Section of Volcanic Neck at 'S Airde Beinne, near Tobermory, Mull. *aa*, bedded basalts; *bb*, bedded basalts altered along the side of vent; *cc*, dolerite.

augite, skeleton-forms and microlites of felspar, sometimes in stellate aggregates, as well as club-shaped, cruciform, arrow-headed, and often crested microlites of magnetite.

Towering prominently above the flat basalt sheets, this neck has an oval form, measuring about half a mile in length by a quarter of a mile in breadth. Its central portion, however, instead of rising into a rugged hill-top, as in all the other instances known to me, sinks into a deep hollow, which is filled with water, and reminds one of a true crater-lake. The middle of the neck is thus concealed from view, and we can only examine the hard prominent ring of dolerite that surrounds the tarn. That the material

* *Quart. Jour. Geol. Soc.*, xxx. (1874) p. 264.

occupying the hollow must be softer than that of the ring is obvious, for great as is the temptation to look on this as a crater-lake, we must admit that what we now see is not the original surface, but has been exposed after the removal of possibly hundreds of feet of overlying material. The present lake-basin, whether or not it may represent a former crater-lake, is undoubtedly due to erosion. Possibly some more easily removable agglomerate may here occupy the centre of the volcanic pipe.

One of the most interesting features of this vent is to be found in its relation to the surrounding basalts. The marginal parts of the rock along the line of contact are much finer in grain than the rest, and have obviously cooled more rapidly. The contrast between them and the ordinary dolerite of the centre, however, cannot be properly understood, except in thin sections under the microscope. Dr HATCH observes that, in place of the structure above described, the marginal parts show an absence of the ophitic grouping except in small isolated patches. Instead of occurring in large grains or plates enveloping the felspars, the augite is found in numerous small roundish grains, together with grains of magnetite, in equal abundance and of similar size. The felspars are spreckled over with opaque particles; olivine was not detected.

For miles around the vent, the plateau-rocks are of the usual type—black, compact, sometimes amygdaloidal, alternating with more coarsely crystalline decomposing bands, the separation between different sheets being often marked by the ordinary red ferruginous partings. But around the margin of the neck, they have undergone a remarkable metamorphism. The portions of them which adhere to the outer wall of the neck have lost their distinct bedding, and have been, as it were, welded together into an indurated compact, black to dull-grey rock, so shattery and jointed that fresh hand-specimens, three or four inches in length, are not easily obtainable. Especially marked is one set of joints which, running approximately parallel, cause the rock to split into plates or slabs. These joints are sometimes curved. Yet, in spite of the alteration from its normal character, the basalt retains in places some of its more usual external features, such, for instance, as its amygdaloidal structure, the amygdules consisting of calcite, finely acicular mesotype, and other minerals.

Examined under the microscope, this altered basalt presents "a confused aggregate of colourless microlites (felspar ?) and innumerable minute granules of magnetite, these two constituents being very unequally distributed. Sometimes the colourless portions preponderate, in other places the opaque granules are heaped together in black patches, which may possibly mark the position of fused augites" (Dr HATCH).

In the zone of contact-metamorphism around some of the volcanic pipes in the plateaux, we see changes analogous to, but less developed than, those which have been superinduced on so large a scale round the great eruptive bosses of gabbro, granophyre, &c., that have broken up the terraced basalts along the west coast of Scotland. I shall accordingly return to this subject in connection with the phenomena presented by these younger rocks.

(*b*) *Vents filled with Agglomerate.*—Though much less frequent than the necks of dolerite, those filled with fragmentary materials bring before us, perhaps more vividly, the volcanic conditions in which they were formed. The agglomerate is generally exceedingly coarse, and without any trace of structure. Blocks of all sizes up to masses some yards in length, and of the most diversified materials, both volcanic and non-volcanic, are dispersed confusedly through a granular paste of similar miscellaneous composition.

One of the most instructive examples has been already alluded to as occurring at the island of Carrick-a-raide, on the north coast of Antrim. It forms that island, and a portion of the opposite mainland. Its visible mass is about 1000 feet in diameter, but the boundaries, except on the land side, are concealed by the sea. The material filling up this vent is a coarse agglomerate, in which blocks and bombs of basalt, with pieces of chalk and flint, are stuck at all angles in a dull dirty-green granular tuff. Some large and small intrusions of basalt rise through it. Owing partly to these intrusions, and partly to the grass-covered slope that separates it from the line of cliff, the actual contact of this neck with the volcanic beds of the escarpment cannot be seen. I have no doubt, however, that the tuff, which has already been referred to as so conspicuous a member of

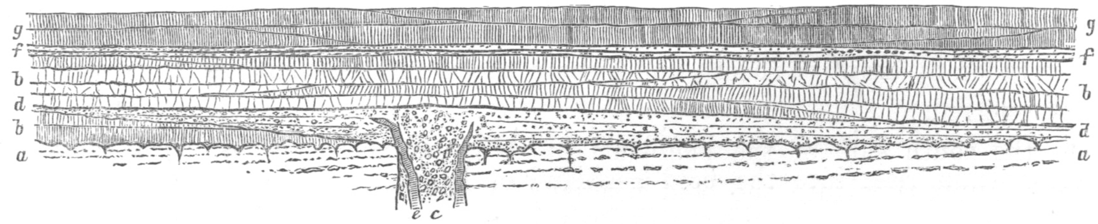


FIG. 29.—Diagram to show the probable relation of the Neck at Carrick-a-raide, Antrim, to an adjacent group of Tuffs. *aa*, Chalk; *bb*, Lower group of bedded basalts; *c*, Vent of Carrick-a-raide, filled with coarse volcanic agglomerate; *dd*, bedded tuffs; *ee*, large veins of basalt traversing the agglomerate; *ff*, zone of tuffs and pisolitic iron ore; *gg*, Upper group of bedded basalts.

the series here, was discharged from this vent.* The materials are as usual coarser in the pipe than beyond it, but the finer portion or matrix of the agglomerate is similar to many bands of the tuff. The structure of the locality may be diagrammatically represented as in fig. 29. The bedded tuff is thickest in the neighbourhood of the vent, and gradually dies away on either side of it.

But another important inference may be drawn from this locality. I have already pointed out that the lower basalts here reach their minimum thickness. Their basement beds thin away towards the vent as markedly as the tuff thickens. Obviously they cannot have proceeded from that point of eruption. Yet, that they had begun to be poured out before the discharge of the tuff, is shown by their underlying as well as overlying that rock, though westward, owing to the thinning away of the undermost basalts, the tuff comes to lie directly on the Chalk. Hence, we may legitimately infer the existence of one or more other vents in the neighbourhood that supplied the sheets of the lower basalts.

In the promontory of Ardnamurchan, where the basalt-plateau has been so obscured

* See Explanation of Sheets 7 and 8, *Geol. Survey of Ireland* (1888), p. 31.

by later intrusions of crystalline rocks and reduced to such a fragmentary condition by denudation, some interesting examples of agglomerate necks have been laid bare. The largest of these occurs on the north shore at Faskadale. Cut open by the sea for more than a quarter of a mile, this neck is seen to be filled with a coarse agglomerate, composed mainly of basalt-blocks and débris, but crowded also with angular and subangular pieces of different close-grained felsitic and porphyritic rocks belonging to the acid series to be afterwards described.* Some of these stones exhibit a very perfect flow-structure, and closely resemble certain fine-grained flinty intrusive rocks in Mull, to which allusion will subsequently be made. The matrix of the agglomerate is of the usual dull dirty-green colour, but is so intensely indurated that on a fresh fracture it can hardly be distinguished from some of the crystalline rocks of the locality. The neck is pierced in all directions with dykes and veins of basalt, dolerite, gabbro, and felsitic rocks. Similar intrusions continue and increase in numbers further west until the cliffs become a labyrinth of dykes and veins running through a mass of rock which appears to consist mainly of dull dolerites and fine gabbros. Though the relations of this vent to the plateau-basalts are not quite plain, the agglomerate seemed to me to rise out of these rocks. At least the basalts extend from Achateny to Faskadale, but, as they are followed westwards, they are more and more invaded by eruptive sheets, and assume the indurated character to which I have already referred.

On the south side of the peninsula of Ardnamurchan, another neck, noticed by Professor JUDD, rises into the bold headland of Maclean's Nose, at the mouth of Loch Sunart, and affords better evidence of its relation to the bedded basalts. It measures about 1000 yards in length by 300 in breadth, and its summit rises more than 900 feet above the sea, which washes the base of its southern front. It is filled with an agglomerate even coarser than that on the northern coast. The blocks are of all sizes, up to eight or ten feet in diameter. By far the largest proportion of them consists of varieties of basalt, slaggy and vesicular structures being especially conspicuous. There are also large blocks of different porphyries and felsitic rocks like those just referred to, a porphyry with felspar crystals two inches long being particularly abundant. All the stones are more or less rounded, and are wrapped up in a dull-green compact matrix of basalt-débris. There is no stratification or structure of any kind in the mass. Numerous dykes or veins, some of basalt, others of a porphyry, resembling that of Craignure, in Mull, traverse the agglomerate.

The position of this vent, with reference to the surrounding rocks, will be best understood from the map (Plate I.), and from the subjoined section (fig. 30). On the

* One of these felsites when viewed under a high magnifying power is seen to present an abundant development of exceedingly minute micropegmatite arranged in patches and streaks parallel with the lines of fluxion structure in the general cryptocrystalline ground mass. The close relationship between the felsites, quartz-porphyries, and granophyres will be afterwards pointed out in the description of the acid rocks. It is remarkable that, though these rocks occur abundantly in fragments in the volcanic necks and agglomerates of the plateaux, not a single instance has been observed of their intercalation as contemporaneous sheets among the basic lavas. An analogous case of the interstratification of felsitic tuffs among basic lavas occurs in the volcanic series of the Old Red Sandstone of central Scotland.

eastern side, the agglomerate can be seen to abut against the truncated ends of the flat beds of the plateau-basalts, which are of the usual bedded compact and amygdaloidal character. There can be no doubt, therefore, that the vent has been opened through these basalts. But it will be observed that the latter belong to the lower part of the volcanic series. These lowest sheets are exposed on the slope, resting upon yellowish and spotted grey sandstone, with seams of jet and a reddish breccia, which, lying in hollows of the quartzites, quartz-schists, and mica-schists, form no doubt the local base of the Jurassic rocks of the district. Hence, the vent, though younger than the older sheets of the plateau, may quite well be contemporaneous with some of the later sheets.

An interesting feature at this locality is the peculiar grouping of some of the large dykes in the area around the agglomerate. They run in the direction of the vent, and one or other of them may represent the fissure or fissures on which the volcanic orifice was blown open to the surface. Another notable element in the geological structure of the ground is the vast amount of intrusive material, both in dykes and sheets, which has been erupted. The intrusive sheets of Ben Hiant form the most prominent eminence in

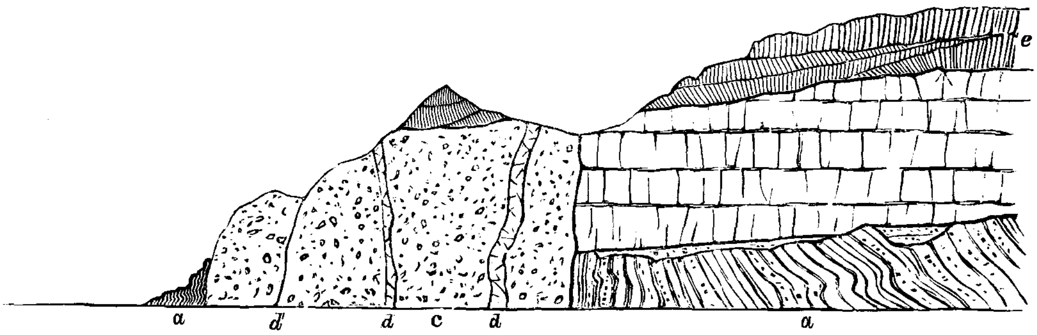


FIG. 30.—Section of agglomerate Neck at Maclean's Nose, Ardnamurchan. *aa*, Quartzites and schists; *b*, bedded basalts lying partly on the schists and partly on patches of Jurassic sandstones that occupy hollows of the older crystalline rocks; *c*, agglomerate; *dd*, dykes and veins traversing the agglomerate; *e*, dolerite sheets of Ben Hiant.

this part of Ardnamurchan. Reserving them for description in a later part of this memoir, I will only remark here that they partly overlie the agglomerate, and are therefore to some extent at least younger than the vent. They belong to that late stage in the history of the basalt-plateaux when the molten material, no longer getting ready egress to the surface, forced its way among the rocks about the base of the bedded basalts, and more especially on the sites of older vents, which were doubtless weak places, where it could more easily find relief.

By far the largest mass of agglomerate in any of the Tertiary volcanic areas is that which occurs on the north side of the main valley of Strath, in Skye.* Unfortunately, it has been so seriously invaded by the eruptive rocks of the group of the Red Hills, that

* This extensive mass was not separated from the "syenite" of the Red Hills by MACCULLOCH. VON OEYNHAUSEN and VON DECHEN noticed it as a conglomerate with quartz pebbles, but did not realise its volcanic nature (*Karsten's Archiv*, i. p. 90). In my map of Strath (*Quart. Jour. Geol. Soc.*, xiv. plate i.) I distinguished it from the rock of the Red Hills, but no name for it appears in the legend of the map, nor is it referred to in the text. Its character as a true volcanic agglomerate was recognised by Professor JUDD, *Op. cit.*, p. 255. See Plate II. of the present memoir.

its original dimensions and its relations to the surrounding rocks, especially to the bedded basalts, are much obscured. It can be followed continuously from the lower end of Loch Kilchrist along the southern slopes of Beinn Dearg Bheag round to the western roots of Beinn Dearg Mhor—a distance of more than two miles in a straight line, and from Kilbride to the flank of Beinn na Caillich above Coire-chat-achan—a direct distance of two miles and a quarter. A similar rock, possibly a portion of the same mass, appears in Creagan Dubha, on the north side of the Red Hills. If the whole of this agglomerate forms part of one originally continuous mass, the vent must have been upwards of two miles in diameter. There may, however, have been two or three closely adjacent vents. The Beinn na Caillich patch, for example, appears to belong to a different area, and that of Creagan Dubha may also be distinct. But there seems no reason to doubt that the mass which forms Cnoc nam Fitheach, and all the long declivity on the southern flank of Beinn Dearg Bheag, occupies part of the site of a single volcanic funnel, which was almost two miles in diameter.

This agglomerate is a coarse tumultuous assembage of blocks and bombs, embedded in the usual dull, dirty-green matrix. Among the stones, scoriaceous, vesicular, and amygdaloidal basalts are specially abundant; also pieces of various quartz-porphyries, among which a black felsite like that of Mull may often be recognised. In some places, large masses of altered Lower Silurian limestone and quartzite are included; in others, pieces of yellow sandstone and dark shale (Jurassic). The rock is wholly without stratification or structure of any kind. On the north-west side of Loch Kilchrist, indeed, it weathers into large tabular forms, the parallel surfaces of which dip to S.W.; but this is probably due only to jointing. Here and there, dykes of basalt cut the rock in a general north-westerly direction, but their number is remarkably small when compared with the prodigious quantity of them in the limestone at the bottom and opposite side of the valley, some of which may possibly mark the fissure of the vent. More abundant and extensive are the masses of granophyre that rise more particularly along the outer margin of the vent. These are doubtless connected with the great boss that forms the Red Hills, of which further details will be given in a subsequent section of the paper.

The important question of the relation of this huge vent to the plateau-basalts does not admit of satisfactory treatment, owing to destruction of the evidence by the intrusion of the granophyre and likewise to enormous denudation. Nevertheless, some traces still remain to indicate that the basalts once stretched over the site of the vent, which probably rose through them. Looking westward from the flanks of Beinn Dearg Bheag to the other side of Loch Slapin, the geologist sees the bold basalt-escarpment of Strathaird presenting its truncated beds to him at a distance of only two miles. That these beds were once prolonged eastwards beyond their present limits is obvious, and that they stretched at least over these two intervening miles can hardly be doubted. But we can still detect relics of them on the flanks of Beinn Dearg. As we follow the agglomerate round the margin of the granophyre that mounts steeply from it, we lose it here and there under beds of amygdaloidal basalt. The rocks next the great eruptive mass of the mountain are so indurated and shattered that it is difficult to separate them from each other and determine their relative positions. But, so far as I could ascertain, these basalts are fragments of beds that overlie the agglomerate (fig. 31). This is not the only place along the flanks of the Red Hills where portions of the bedded basalts have survived. Other localities will be subsequently alluded to.

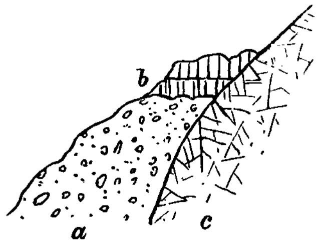


FIG. 31.—Diagram to show the probable relations of the rocks on the southern flank of Beinn Dearg Bheag. *a*, agglomerate; *b*, amygdaloidal and compact basalt-rocks; *c*, granophyre.

The great vent of Strath has been drilled through the Lower Silurian limestone, and as the result of protracted denudation it now towers steeply five or six hundred feet above that formation on the floor of the valley. Of the material discharged from it over the surrounding country no certain trace now remains. We may infer from the nature of the rock which fills it that towards the end, if not from the beginning of its activity, its discharges consisted mainly of dust and stones. A crater, of which the pipe was two miles in diameter, must surely have sent its fragmentary materials far and wide over the surrounding region. But on the bare platform of older rocks to the south not a vestige of these erupted materials can now be found. Westward the escarpment of Strathaird remains to assure us that no thick showers of ashes fell at even so short a distance as two miles, either before or during the outpouring of the successive basalt sheets still remaining there. We may therefore conclude with some confidence that here, as at Ardnamurchan, the vent must be younger than at least the older parts of the basalt-plateau. Unfortunately the uprise of the large bosses of granophyre that stretch from the Red Hills to Loch Sligachan has entirely destroyed the vent and its connections in that direction. There is no certain proof that any molten rock ever issued from this orifice, unless we suppose the fragmentary patches of amygdaloid on the southern flank of Beinn Dearg Bheag to be portions of flows that proceeded from this centre of eruption. I have little doubt that the basalt-plateau which still remains in Strathaird formerly extended eastwards over Strath and northwards across the site of the Red Hills and Cuillins, joining on to the continuous tableland north of Lochs Brittle and Sligachan. How much of the plateau had been built up here before the outburst of the vent can hardly be conjectured. The agglomerate may possibly, of course, belong to the very latest period of the plateau-eruptions, or even to a later phase of Tertiary volcanic history. The impression, however, made on my mind by a careful study of the evidence from this and the other districts is that the necks of agglomerate, like those of dolerite and basalt, really belong to different epochs of the plateau period; that they mark for us some of the vents from which the materials of the plateaux were emitted.

The example of Carrick-a-raide is peculiarly suggestive when we regard it in connection with the great Strath vent. Already the progress of denudation has removed at least half of the layer of dust and stones which, thrown out from that little orifice, fell over the bare chalk-wolds and black basalt-fields of Antrim. The neck that marks the position of the volcanic funnel has been largely cut away by the waves, and is almost entirely isolated among them. But the march of destruction has been greater in Skye. The connection between the vent and the materials ejected from it has been entirely removed, and we can only guess from the size of the remaining neck what may have been the area covered by the discharges from this largest of all the volcanic cones of the Inner Hebrides.

In bringing this part of my subject to a close, I would repeat that the distinctive characters of the basalt-plateaux lead us to seek the modern analogies to these volcanic phenomena, not in large central cones discharging streams of lava in different directions like Vesuvius or Etna, but in those basalt-regions where the lavas have issued from innumerable minor and sometimes almost imperceptible vents.* I have already referred to a journey made by me in 1879 through some of the vast basalt-fields of Western America, and to the light which I thereby gained on the history of the youngest volcanic tracts of Britain. The basalt of Idaho stretches out as a vast and apparently limitless plain. Along its northern boundary, this sea of black lava runs up the valleys and round the promontories of the older trachytic hills, with almost the flatness of a sheet of water. It has been deeply trenched, however, by the streams that wind across it, and especially by the Snake River, which has cut out a gorge some 700 feet deep, on the walls of which the successive beds of basalt lie horizontally one upon another, winding along the curving face of the precipice exactly as those of Antrim and the Inner Hebrides do along their sea-worn escarpments. Here and there, a low cinder-cone on the surface of the plain marks the site of a late outflow. One is struck, also, with the singular absence of tuffs and volcanic conglomerates. The basalts appear to have flowed out stream after stream with few fragmentary discharges.

These characteristic features of one distinctive type of volcanic action have been repeated over a vast region, or rather a whole series of regions, in Western America, the united area of which must equal that of a considerable part of Europe. From Idaho, the basalt-fields may be followed southwards interruptedly into Utah and Nevada, and across the great plateau-country of the cañons into Arizona and New Mexico, northwards into Montana, and westwards into Oregon. The tract which has as yet been most carefully traversed and described is probably that of the high plateaux of Utah and Arizona. Thus on the Uinkaret plateau, which measures some 45 to 50 miles in length by 8 to 12 in breadth, a thick sheet of basalt has been spread consisting of many successive flows.

* In this connection I may again refer to HOPKINS's *Researches in Physical Geology*, where the conditions of the problem here discussed have been distinctly realised. Speaking of the ejection of lava from a number of fissures, he remarks that the imperfect fluidity of the melted material "would seem to require a number of points or lines of ejection as a necessary condition." "If there were only a single centre of eruption, a bed of such matter approximating to uniformity of thickness, could only be produced on a surface of a conical form." "Where no such tendency to this conical structure can be traced, it would probably be in vain to look for any single centre of eruption. On the supposition, too, of ejection through continued fissures, or from a number of points, that minor unevenness of surface which must probably have existed under all circumstances during the formation of the earth's crust, would not necessarily destroy the continuity of a comparatively thin extensive bed of the ejected matter, in the same degree in which it would inevitably produce that effect in the case of central ejection" (*Cambridge Phil. Trans.*, vi. (1835), p. 71).

Between 160 and 170 separate cones have been counted on this area, most of them quite small, mere low mounds of scoriæ, though a few reach a height of 700 or 800 feet, with a diameter of a mile. From three to seven or eight may be found in a row, as if springing from a single line of fissure. But generally the grouping is quite irregular.* My friend Captain C. E. DUTTON, from whose admirable memoir these details are quoted, remarks further that among the Utah plateaux no trace of a cone is to be found at or near some of the most recent basalt-fields, and that the most extensive outpours are most frequently without cones. "The lavas," he adds, "appear to have reached the surface and overflowed like water from a spring, spreading out immediately and deluging a broad surface around the orifice." † The deep gorges cut by the rivers through these thick accumulations of horizontal or nearly horizontal basalts, have here and there revealed the parallel dykes that traverse the rocks, and in at least one case have shown the dyke running for half a mile up a cliff and actually communicating with a crater of scoriæ at the top. ‡ Again, in New Mexico, Captain DUTTON noticed vast tracts of younger basalt, about which "a striking fact is the entire absence of all distinguishable traces of the vents from which they came. Some of them, however, indicate unmistakably their sources in small depressed cones of very flat profiles. No fragmental ejecta (scoriæ, lapilli, &c.) have been found in connection with these young eruptions." § Such I believe to have been the general conditions under which the basalts of the Tertiary plateaux of the British Isles were also erupted.

§ 4. INTRUSIVE SHEETS OR SILLS OF THE PLATEAUX.

There is one further part of the structure of the basalt-plateaux of which some account must now be given. In a former paper, I have shown that at different parts of the basalt series, but especially at their base and among the stratified rocks underneath them, sheets of basalt and dolerite occur which, though lying parallel with the stratification of the volcanic series, are not truly bedded masses, but are intrusive sills, and therefore of younger date than the rocks between which they lie. || The non-recognition of their intrusive and subsequent nature led to these sheets being regarded as proofs of the intercalation of volcanic beds in the Jurassic series of western Scotland. There is, however, not the least trace of the true interstratification of a volcanic band in any part of that series, every apparent example being due to the way in which intrusive sheets simulate the characters of contemporaneous flows.

If such sheets had been met with only at one or two localities, we might regard them as due to some mere local accident of structure in the overlying crust through which the erupted material had to make its way. But when we find them everywhere, from the

* C. E. DUTTON, "Tertiary History of the Grand Cañon District," *U.S. Geol. Survey* (1882), p. 104.

† C. E. DUTTON, "Geology of the High Plateaux of Utah," *U.S. Geol. Survey of the Rocky Mountain Region* (1880), pp. 198, 200. See also pp. 232, 234, 276 of the same Monograph for additional examples.

‡ *Tertiary History of the Grand Cañon*, &c., p. 95.

§ *Nature*, xxxi. (1884) p. 89.

|| *Quart. Jour. Geol. Soc.*, xxvii. (1871) p. 296.

far headlands of Skye to those of Antrim, it is obvious that they must be due to some general cause, and that they contain the record of a special period or phase in the building up of the volcanic tablelands. I will first describe some typical examples of them from different districts, and then discuss their probable relations with the other portions of the plateaux.

First to be examined, and now most familiar to geologists, are the remarkable sheets that underlie the plateau of Antrim, and project at various parts of the picturesque line of coast from Portrush to Fair Head. From the shore at Portrush came the evidence that was supposed to prove basalt to be a rock of aqueous origin, inasmuch as shells were obtained there from what was believed to be undoubtedly basalt. The long controversy to which this supposed discovery gave rise is one of the most curious in the history of geology.* Fellows of this Society have cause to remember with pleasure that it was one of their predecessors, the illustrious PLAYFAIR, who showed the pretended basalt to be in reality highly indurated shale, and hence that, instead of furnishing proof of the aqueous formation of basalt, the Portrush sections only contributed another strong confirmation of the Huttonian theory, which claimed basalt to be a rock of igneous origin.

It is now well known that the rock which yielded the fossils is a Liassic shale, that it is traversed by several sheets of eruptive rock, and that by contact-metamorphism it has been changed into a highly indurated substance, breaking with a splintery, conchoidal fracture, but still retaining its ammonites and other fossils. The eruptive material is a coarse, distinctly crystalline dolerite, in some parts of which the augite with its penetrating lath-shaped crystals of plagioclase is remarkably fresh, while the olivine has begun to show the serpentinous change along its cracks. † This rock has been thrust along the bedding planes of the shales, but also breaks across them, and occurs in several sheets, though these may all be portions of one subterranean mass. Some of the sheets are only a few inches thick, and might at first be mistaken for sedimentary alternations in the shale. But their mode of weathering soon enables the observer readily to distinguish them. It is to be noticed that these thin layers of eruptive material assume a fine grain, and resemble the ordinary dykes of the district. This closeness of texture, as GRIFFITH long ago pointed out, ‡ is also to be noticed along the marginal portions of the thicker sheets, where they lie upon or are covered by the shales. But away from the surfaces of contact, the rock assumes a coarser grain, insomuch that in its thickest mass it presents crystals measuring sometimes an inch in length, and then externally resembles a gabbro. A more curious structure is shown in one of these coarsely crystalline portions by the occurrence of a band a few inches broad which is strongly amygdaloidal, the cells, sometimes three inches or more in diameter, being filled with zeolites. § The general dip of

* For an excellent summary of it and an epitome of the descriptions of the Portrush section, see the *Report on the Geology of Londonderry*, &c., by J. E. PORTLOCK (1843), p. 37.

† Dr F. HATCH, Explanation of Sheets 7 and 8, *Geol. Survey of Ireland*, p. 40.

‡ "Address to Geological Society of Dublin, 1835," p. 13, *Jour. Geol. Soc. Dublin*, vol. i. The varieties of the Portrush rock were described by the late Dr OLDHAM, in Portlock's *Report on the Geology of Londonderry*, p. 150; see also the same work for Portlock's own remarks, p. 97.

§ For a list of the minerals in this rock, see OLDHAM, *op. cit.*, p. 151.

the shales and of the intrusive sheets which have been injected between them is towards the east. From underneath them a thick mass of dolerite rises up to form the long promontory that here projects northwards from the coast-line, and is prolonged seawards in the chain of the Skerries.

An interesting feature of the Portrush sections is the clear way in which they exhibit the phenomena of segregation-veins—so characteristic of the thicker and more coarsely crystalline intrusive sheets. These veins or seams differ from the rest of the rock mainly in the much larger size and more definitely crystalline form of their component minerals. Though sharply defined, when looked at from a little distance, they are found on closer inspection to shade into the surrounding rock by a complete interlacing of crystals. On the shore, they can be seen to lie on the whole parallel with the bedding of the sheets in which they occur, but without rigidly following it, since they undulate and even ramify. A good section across their dip has been exposed in a quarry near the end of the promontory, and shows that they are considerably less regular than the plan of their

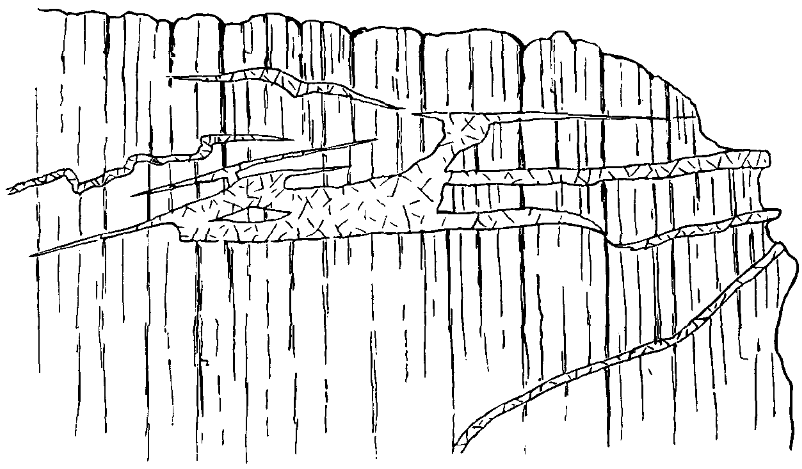


FIG. 32.—View of Segregation Veins in dolerite of an Intrusive Sheet, Portrush, Antrim.

outcrop on the shore would have led us to anticipate. The accompanying drawing (fig. 32) represents the veins laid bare on a face of rock 9 feet in length by 5 feet in height. It will be seen that while there is a general tendency to conform to the dip-slope, which, is here from right to left, the seams or layers unite into a large rudely bedded mass, which sends out processes across the bedding. The peculiar aggregation of minerals which distinguishes such segregation veins is perhaps best seen at Fair Head, and I reserve for the description of that locality what I have to say on the subject, only remarking with regard to the Portrush rock that the felspar shows a disposition to collect in the centre of the veins with the augite and the other dark minerals at the outer margins.

The contact-metamorphism at this locality is of more historical interest in connection with the progress of geological theory than of scientific importance. It consists mainly in an intense induration of the argillaceous strata. These pass here from their usual condition of fissile, laminar, dull, dark shales into an exceedingly compact, black, flinty substance, which in its fracture, colour and hardness reminds one of Lydian stone. Yet the ammonites and other organic remains have not been destroyed. They are preserved in pyrites.

Of all the examples of intrusive sheets of Tertiary age in Britain there is none more imposing than that of the noble range of precipices which form the promontory of Fair Head. Leaving out of account the minor masses of eruptive rock which occur underneath it, we find the main sheet to extend along the coast for nearly four miles, to rise to a height of 636 feet above the sea, and to attain a maximum thickness of 250 feet. This enormous bed dies out rapidly both to the east and west, and seems also to thin away inland. Seen from the north, it stands upon a talus of blocks as a sheer

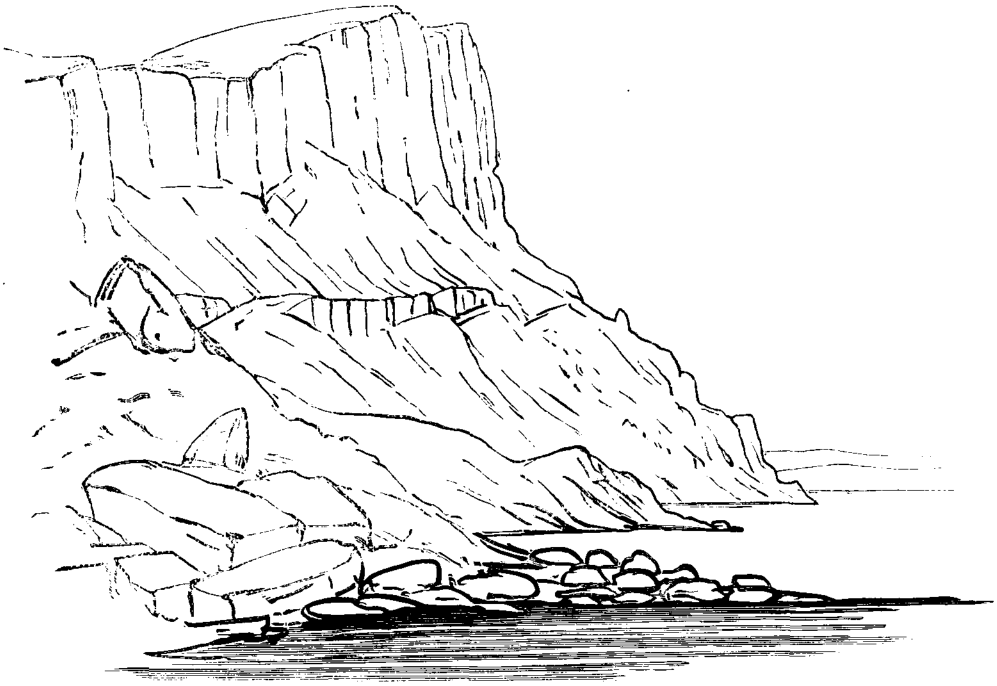


FIG. 33.—View of Fair Head from the East, showing the main upper intrusive sheet and a thinner sheet cropping out along the talus slope.

vertical wall, 250 feet high, and the rude prisms into which it is divided are continuous from top to bottom (fig. 33). So regular is this prismatic structure, and so much does it recall the more perfect columnar grouping of the basalts, that at a little distance we can hardly realise the true scale of the structure. It is only when we stand at the base of the cliff or scramble down its one accessible gully, the "Grey Man's Path," that we appreciate how long and thick each of the prisms actually is.

The rock composing this magnificent sheet is a coarsely crystalline, ophitic, olivine-dolerite.* The same diminution of the component crystals, which is so marked along the

* Professor JUDD has described what he calls a "glomero-porphyritic structure" in this rock (*Quart. Jour. Geol. Soc.*, xlii. (1886) p. 71).

margins of the eruptive masses at Portrush, is strikingly exhibited at Fair Head. For about 18 or 20 inches upward from the bottom, where the bed rests on the black, Carboniferous shales, the dolerite is dark and finely crystalline, weathering spheroidally in the usual manner. But immediately above that bottom layer of closer grain the normal coarsely crystalline texture rapidly supervenes. A similar closeness of grain is observable at the surfaces of contact where the sheet splits up on its western border.

Nowhere, so far as I know, can the phenomena of segregation veins be so instructively studied as along the abundant exposures of this great sheet. The veins are most conspicuous where the rock occurs in thickest mass. They vary up to three or four feet in thickness, and, as at Portrush and elsewhere, lie on the whole parallel to the upper and under surfaces of the sheet. An erroneous impression may be conveyed by the term "veins" applied to them. They are quite as much layers, parallel on the whole with the bedding of the sheet, yet not adhering rigidly to one plane, but passing across here and there from one horizon to another. That they are not due to any subsequent protrusion of younger material through the main sheet is made manifest by the thorough interlocking of their component crystals with those of the body of the rock in which they lie. They consist of an exceedingly coarse aggregate of crystals, or rather of crystalline lumps of the minerals that constitute the general mass of the rock, the felspar and augite showing the ophitic intergrowth of the main rock, but on a far larger scale. Some of the pieces of augite measure two inches or more in diameter.

This great Fair Head sheet lies upon Carboniferous strata, but that it is to be classed with the Tertiary volcanic series is, I think, demonstrated by its relations to the Chalk at its eastern end. It has there broken through that rock, and converted it for a short distance into a white, granular marble. But it is at the western side that the most interesting sections occur to show the truly intrusive nature of the mass. The rock there splits up into about a dozen sheets, which, keeping generally parallel with each other, have forced their way between and partly across the bedding planes of the Carboniferous shales (fig. 34). In this way the huge, unbroken mass, 250 feet thick, subdivides itself and disappears in a few hundred yards, though it continues a little further inland, and approaches the shore again half a mile to the south-west. Further evidence of the intrusive nature of this rock may be observed along the base of the precipice, where at least one sheet 70 feet thick diverges from the main mass and runs eastwards between the Carboniferous shales (fig. 33). At the contact with the eruptive rock the shales are everywhere much indurated.

All through the Inner Hebrides the base of the basalt series generally presents abundant examples of intrusive sheets. I have already alluded to this fact as an explanation of the conclusion to which geologists were led, that in Skye and elsewhere the basalts are interstratified with the Jurassic rocks, and are consequently of Jurassic age. It was MACCULLOCH who first described and figured in detail these proofs of intrusion. His well-known sections in plate xvii. of the illustrations of his work on the *Western*

Islands have been repeatedly copied, and have served as typical figures of intrusive igneous rocks.

Though none of the examples in the Inner Hebrides attain the dimensions of the Fair Head sheet, still they present a much greater variety of rock and of geological structure than is to be found in Antrim. I have already referred to the base of the thick, overlying, basalt-plateaux in Scotland, as a horizon along which a prodigious quantity of eruptive material has subsequently been injected. Part of this material consists of basic rocks in the form of dykes, veins, or sills; part of it is included in the acid group, and comprises veins, sheets, and bosses of granitoid, felsitic, rhyolitic, trachytic, and pitchstone rocks. With regard to the basic sheets (dolerites, basalts, &c.) which occur on this horizon, I would remark that while in western Scotland the Antrim type is also found, the vast majority of the sheets belongs to a quite distinct type. For the sake of continuity, I may first describe some examples of the occurrence of thick, coarsely crystalline, rapidly diminishing sills like those of the north coast of Antrim.

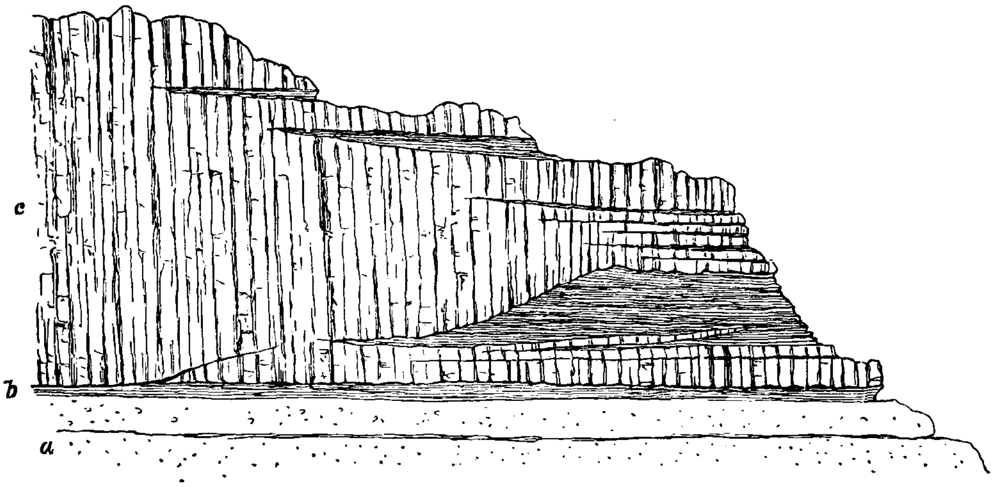


FIG. 34.—Section at Farragandoo Cliff, west end of Fair Head, showing the rapid splitting up and dying out of an Intrusive Sheet. *a*, Carboniferous sandstone; *b*, Carboniferous shale; *c*, intrusive sheet.

On the coast of Skye, between Lochs Slapin and Eishort, the prominent headland of Suisnish has long been known to geologists from the section of it given by MACCULLOCH as an instance of the connection between overlying rocks and dykes. I have already alluded to it in that relation, and refer to it again as an example of one of the thicker intrusive sheets of the Inner Hebrides. Denudation has proceeded so far in that district of Skye that the whole of the volcanic plateau has been stripped off, and we have only some of the underlying sills left, with the platform of older rocks between which and the vanished basalts they were injected. Most of these sills consist of granophyres belonging to the acid group of rocks to be afterwards described. But among them there occur true dolerite sheets not infrequently interposed between the granophyres and the subjacent Lias, and sometimes even intercalated in the former rock. Though at first sight it might be thought that these sills had insinuated themselves after the eruption of the granophyre, and there are instances where this cannot be shown not to be the case, I have obtained so many proofs of the invasion of the basic by the acid rock that I have no doubt the former is as a general rule the older of the two. The Suisnish headland exhibits the structure represented in fig. 14. For about 300 feet above the sea-level the steep grassy slope shows outcrops of the dark, sandy shales and yellowish brown, shaly sandstones of the Lias which form the range of cliffs to the eastward. These gently inclined strata are cut through by many vertical basalt-dykes, some of which intersect each other, but among which by far the largest is the mass shown in the figure. This broad dyke consists of a dolerite, the largely crystalline texture of which marks it off at once from the others, which are of the usual dark, heavy, fine-grained type, with an occasional andesitic and porphyritic variety. Traced up from the sea-margin, the dyke loses itself in a talus of blocks from the cliff above, so that its actual junction with the mural front of the sill cannot be seen. But that it joins that mass, with which it agrees in petrographical characters, hardly admits of question. The cliff consists of a thick sheet of coarsely crystalline dolerite (*c* in fig. 14), which in its general aspect at once recalls the rock of Fair Head. It varies considerably in texture, some parts of the mass are exceedingly coarse, like the Skye gabbros, and present a fibrous structure in their augite resembling that of the diallage in these rocks; other portions assume the compactness of basalt. A specimen of medium grain under the microscope shows the typical ophitic structure so generally found among the dolerites both of the plateaux and of the intrusive sheets. This sill must be about 200 feet thick, and like the rock at Fair Head is traversed from top to bottom by joints that divide it into prisms. It appears to bifurcate eastward, one portion running with a tolerably uniform thickness of a few feet as a prominent band at the top of the shales and sandstones, the other slanting upwards and gradually thinning away in the granophyre.

Towards its base, near the contact with the underlying shales, the rock as usual becomes finer grained, and the thin band just referred to resembles in texture one of the wider basalt-dykes. Westwards the rock can be followed round the top of the grassy slopes formed by the decay of the shales. Though concealed by intervals of moorland and peat, it is visible in the stream sections, and I think must be continuous, as a band only a few yards thick, round the northern side of the hills as far as Beinn Bhuidhe, where a similar sill makes a prominent crag. Its total area measures a mile and a quarter in length by half a mile in breadth. The granophyre which overlies it forms part of an interesting series of sheets which I have traced all the way from Suisnish to the braes above Skulamus.

Whether or not the whole sheet of basic rock is continuous, and whether it all proceeded from the great Suisnish dyke, cannot be confidently decided, though from the great thickness of the sill at the dyke, its attenuation outwards from that centre and its uniformity of petrographical character, I am disposed to answer affirmatively. There is no other probable vent to be seen in the neighbourhood, unless a massive dyke that runs from Loch Fada north-westwards into Glen Boreraig can be so regarded.

Another example of the thicker type of sills may be selected from the promontory of Ardnamurchan.* The general form and position of this mass will be understood from the small map in Plate I. Forming the rugged shore for three quarters of a mile, it slopes thence inland in a series of rocky knolls, which in rather less than a mile culminate in the summit of Ben Hiant, 1729 feet above sea-level. The rock which covers this large space is disposed in numerous rude beds, which have a seaward dip of perhaps 15° to 20°. They are distinctly prismatic, and the prisms are not infrequently grouped in fan-shape. They are evidently due to different eruptions, but I observed no trace of any other rock intercalated between them. They are never, so far as I could discover, amygdaloidal nor do they present the ordinary external characters of the beds of the plateaux. They distinctly overlie the bedded basalts on their eastern and southern margins; but westwards they appear to lie transgressively across the edges of these rocks, and to the north-west they rest on quartzites and schists. An outlier from the main mass forms the prominent hill of Srŏn Mhŏr, and can be seen distinctly overlying the bedded basalts as well as the neck of agglomerate already described (fig. 30). The rock of Ben Hiant is for the most part a well crystallised, ophitic olivine-dolerite. A specimen taken from the shore on the west side of the mass was found by Dr HATCH to present under the microscope its augite in large plates, which enclose narrow laths and needles of plagioclase felspar as well as grains of olivine. All the felspars are in lath-shapes, sometimes extremely long and narrow. The iron-ore likewise assumes an ophitic character, enclosing rectangular portions of felspar. Another specimen, taken from the south-east side of the hill, showed under the microscope "a curious intermixture of two different structures. Scattered portions which show the usual ophitic structure, their felspar and augite occurring in large crystals, are, so to speak, imbedded in a ground mass which presents rather a basaltic type, its felspar, augite, and magnetite, in long thin needles, microlites, and other skeleton forms, being enclosed in a dark devitrified base." A third specimen, selected from one of the columnar sheets near the top of Ben Hiant, is "a fine grained dolerite (or gabbro) showing little ophitic structure, the augite occurring in roundish grains, and only slightly intergrown with the felspars, which are more or less lath-shaped. The rock contains a considerable quantity of black iron-ore in irregular grains and some dirty-green viridite." Still another variety of structure occurs in a specimen which I broke from one of the shore crags on the S.W. side of the hill. Under the microscope, it presents a beautiful aggregate of "skeleton crystals and microlites of plagioclase, with here and there a rectangular crystal, long slender microlites of augite, and short serrated microlites of magnetite, the whole being confusedly imbedded in a dark glassy base powdered over with a fine magnetite dust."

In rambling over this Ardnamurchan rock I was often reminded of the great intrusive mass of Fair Head. One of the features in which the rocks of the two localities resemble each other is their tendency to assume a coarsely crystalline texture. In some parts of

* This locality has been described by Professor JUDD, who believed the dolerites to be streams proceeding from a volcanic vent (*Quart. Jour. Geol. Soc.*, xxx. (1874) p. 261).

Ben Hiant the individual crystals reach an inch or more in length. These more largely crystalline portions, however, do not form distinct bands so much as patches in the midst of the general mass; at least I did not notice any examples of such veins of segregation as are so prominent in Antrim.

Owing to the denudation, which has laid this mass bare, no trace now remains of the rocks which covered it. That it is really an intrusive mass and not a superficial outflow, as Professor JUDD supposed, may be inferred from the way it slants across the beds of the plateau, and also from its petrographical characters, in which it agrees with other undoubtedly intrusive rocks of the same series. None of the rocks which unquestionably flowed out on the surface present this coarsely crystalline structure. On the south-east of Ben Hiant, I observed at two places where the bedded basalts could be traced close up to the intrusive mass that the former presented the same dull indurated character which I have referred to as occurring near intrusive bosses on the plateaux. As shown on the small map in Plate I., two marked dykes diverge from the main mass of dolerite and run for some distance north-eastward. One of these, fully a mile long, descends into the valley and rises up into the basalt-plateau on the further side. Possibly these may be two of the feeders from which the thick mass of Ben Hiant was supplied.

But infinitely more frequent in the west of Scotland is the second type of intrusive sheet, where, instead of lying in lenticular, coarsely-crystalline sills, the eruptive rock occurs in thin sheets, interposed with sometimes most deceptive regularity between the bedding planes of the rock which it traverses. It is this type which has become so familiar, from the descriptions and sections of MACCULLOCH, as characteristically given in his account of Skye and in his drawings of the east coast of Trotternish in plate xvii. of his illustrations already cited. The height to which the base of the basalt escarpment rises on that side of the island, and the fine range of cliffs which there underlie it, permit the phenomena of intrusive sheets to be studied better than perhaps anywhere else in Britain. The erupted material has been thrust between the stratification planes of the Jurassic strata, between the strata and the overlying bedded basalts, and between the individual sheets of basalt. As MACCULLOCH well shows, many sheets of intrusive rock, if seen only at one point, might readily be supposed to be regularly interstratified; but perhaps only a few yards distant they may be found to break across the bedding, and to resume their course on a different level.

The phenomena of the eastern coast of Trotternish are repeated on the east side of Raasay, in Eigg, and in Mull. As a single example of them, I may select the accompanying section (fig. 35) from the east side of Eigg. Over the Jurassic sandstones (*aa*) a sheet of basalt (1) four to six feet thick has been injected between the stratification of the sandstones, and another (2) two to four feet thick has forced its way across the middle of one of the bedded basalts (*bb*) in which it bifurcates, and above which comes the thick series of lavas of the plateau (*c*, *d*). In one of the streamlets, which exposes a section of the Jurassic strata below the volcanic escarpment, more than twenty intrusive sheets may be counted among the shales and limestones. They are sometimes not six inches thick, and seldom exceed six or eight feet.*

It is observable generally throughout the west of Scotland, that the rock of the sills is more coarsely crystalline than that of the dykes, which in turn is generally not so fine-grained as that of the bedded basalts, but that the development of the crystalline structure is usually proportionate to the thickness of the mass. On the whole, the thinnest sheets are finest, and the thickest are coarsest in grain. But as they never reach the dimensions of the Antrim mass, they do not present such a largely crystalline texture as can be seen at Fair Head. It is further noticeable that, while they tend to lie between the bedding planes of the rocks which they traverse, they frequently break across them. What is most singular in this respect is their occasional disruption of one of the solid columnar or amorphous basalts, as in the example from Eigg just cited, where one might have supposed that the path of least resistance would have been much more readily found along the line of junction between two beds. Again, the abundance of intrusive sheets about the base of the volcanic plateaux contrasts strongly with their scarcity or absence higher up. We may examine miles of the central and higher parts of the basalt-escarpment without detecting a single example of them, but if the escarpment is cut down to the base we seldom need to search far to find them in numbers.

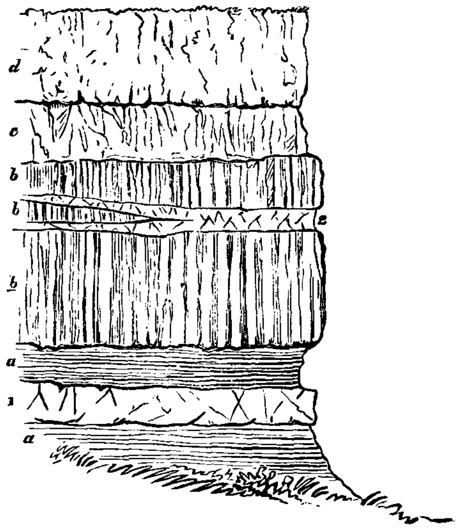


FIG. 35.—Section to show Bedded and Intrusive Sheets, Eigg.

If we consider the facts which have now been adduced regarding the position and structure of the Intrusive Sheets, we are led, I think, to regard these masses as belonging to the history of the basalt-plateaux, but to a comparatively late part of it. They consist of essentially the same materials as the lavas that form these plateaux, though with the differences of structure that the conditions of their production would lead us naturally to expect. Where they occur in thick masses, they have obviously been able to cool much more slowly at some depth beneath the surface than the comparatively thin beds could do that were poured out above ground, and hence they have there assumed a far more largely crystalline texture than was possible for them under other conditions. Their extraordinary number about the base of the basalt-escarpment points, in my opinion, to the increasing difficulty which the gradual thickening of the basalt-series presented to the uprise of molten matter. That the plateaux were rent open and that lava rose in the fissures thus caused, even after a depth of 2000 or 3000 feet of basalt had been piled up, is proved by the height to which dykes can be traced in Mull and elsewhere. But there would no doubt come a time when the vents would grow fewer, and

* *Quart. Jour. Geol. Soc.*, xxvii. (1871) p. 297.

when the pent-up volcanic energy would be unable to open new ones. Through the shattered crust the lava would be forced upwards, but the deep overlying cover of bedded basalts would present a formidable obstacle to its further ascent. Unable to find ample enough egress through such fissures as might be formed in the pile of basalts, the molten rock would seek its lines of least resistance along the planes of the strata and the lower basalt-beds; and there, accordingly, we find the sills in extraordinary profusion. They are no doubt of all ages in the progress of the building up of the volcanic plateaux, but I am disposed to believe that a large number of them may belong to the very latest period of the uprise of basalt within the area of Britain.

In closing this history of the accumulation of the great Tertiary volcanic plateaux of this country, I would remark that as the result of prolonged eruptions from innumerable vents, the depression that stretched from the south of Antrim to the Minch was gradually in large measure filled up. We know that the pile of basalt-sheets reached in some places a depth of more than 3000 feet, and that not improbably it stretched in one continuous field of black lava along the west of Scotland and across the north of Ireland. That the lava spread round the base of the Highland mountains and ran up the Highland glens, much as the sea now does, is made clear from the position of the outliers of it which have been left perched on the ridges of Morven and Ardnamurchan. So far as can now be surmised, these wide Phlegræan fields were only varied by a few volcanic cones scattered over their surface, marking some of the last vents from which streams of basalt had flowed. But the volcanic energy was still far from exhaustion. After the accumulation of such a deep and far extended sea of lava, those underground movements which produced the fissures that served as channels for the uprise of the dykes through all the older rocks continued to show their vigour. The covering of bedded lavas, though several thousand feet thick, was rent open by innumerable long parallel fissures in the prevalent north-westerly direction, up which basic lavas rose to form dykes. Whether the outflow of the bedded basalts had wholly ceased when the last dykes were injected into the plateaux cannot be told. Nor is there any evidence whether it had ended before the next great episode of the volcanic history—the extravasation of the gabbro bosses. All that we can affirm with certainty is, that the formation of north-west fissures and the uprise of basalt in them were repeated, for we find N.W. basalts traversing even the crests of the later eruptive masses of basic and acid rocks. It is difficult to suppose that none of these latest dykes communicated with the surface, and gave rise to cones with the outpouring of basalt and the ejection of dust and stones. But of such later manifestations of volcanic activity on the surface of the plateaux no undoubted trace can now be recognised.

III. THE BOSSES AND SHEETS OF GABBRO.

In singular contrast to the nearly flat basalts of the plateaux, another series of rocks rises high and abruptly above these tablelands into groups of dome-shaped, conical, spiry, and rugged hills. It is these heights which more than any other feature relieve the monotony of the wide areas of almost horizontal stratification so characteristic of the volcanic region of the north-west. Their geological structure and history are much less obvious than those of the bedded basalts. Their mountainous forms at once suggest a wholly different origin. Some portions of them have even been compared with the oldest or Archæan rocks.* That they are really portions of the Tertiary volcanic series, and that they reveal a wholly distinct phase in the history of volcanic action, is now frankly admitted. Whether we regard them from the petrographical or structural point of view, they naturally arrange themselves into two well-defined groups. Of these one consists of highly basic compounds, of which olivine-gabbro is the most prominent. The other comprises numerous varieties—granite, granophyre, felsite, quartz-porphyry, trachyte, pitchstone, and others—all of them being decidedly acid, and some of them markedly so. For reasons which will appear in the sequel, the former group must be considered as the older of the two, and it will therefore be described first.

§ 1. Petrography.

Since the publications of Macculloch, the occurrence of beautiful varieties of highly basic rocks among the igneous masses of the Western Isles has been familiar to geologists. They were named by him "hypersthene rock" and "augite rock," † names which continued in use until 1871, when my friend Professor Zirkel published the results of his tour through the west of Scotland, and showed that the rocks in question were mostly true gabbros. ‡ Since his observations were published some of these rocks have formed the subject of important papers by Professor Judd. §

The general petrographical characters of the gabbro areas of western Scotland may be summarised as follows :—A very considerable variety of petrological structure and chemical composition is observable among the rocks. At the one end of the series are compounds of plagioclase and augite, which, though wanting in olivine, have the general structure and habit of dolerites. At the other end are mixtures wherein felspar is scarce or absent, and where olivine becomes the chief constituent. Between these two extremes are many intermediate grades, of which the most important are those containing the variety of augite known as diallage and also olivine. These are the olivine-gabbros, which form so

* This was my own first impression, when I began, as a boy, to ramble among them. Macculloch had correctly grouped them with the other overlying rocks, and this conclusion was afterwards confirmed by Zirkel.

† *Western Islands of Scotland*, vol. i. pp. 385, 484.

‡ *Zeitschrift. Deutsch. Geol. Gesellsch.*, xxiii. (1871) p. 1.

§ *Quart. Jour. Geol. Soc.*, xli. (1885) p. 354, xlii. (1886) p. 49.

marked a feature in the central parts of the great basic bosses. That some of these varieties of rock pass into each other cannot be doubted. Their distinctive composition and structure appear to have been largely determined by their position in the eruptive mass. The outer and thinner sheets are in great measure dolerites, with little or no olivine. The coarse gabbros are found in the inner portions. Rocks rich in olivine, however, occur at the outer and especially the lower part of the gabbro boss of Rum. The following leading varieties may be enumerated.

Dolerite.—This rock varies from an exceedingly close grain (when it approaches and graduates into basalt) up to a coarse granular crystalline texture, in which the component minerals are distinctly visible to the naked eye. An average sample is found to consist of plagioclase, usually lath-shaped, and crystals or grains of augite with or without olivine. Under the microscope, the different varieties are distinguished by the presence of more or less distinct ophitic structure, the felspar being enveloped in the augite. For the most part they are holocrystalline, but occasionally show traces of a glassy base. Ilmenite is not infrequent, with its characteristic turbid decomposition product (leucoxene). In other cases the iron-ore is probably magnetite. Between the dolerites and gabbros no line of demarcation can be drawn in the field, nor can a much more satisfactory limitation be made even with the aid of the microscope. As a rule, the thickest and largest intrusive masses or bosses are gabbro, those of less size are dolerite, while the smallest (and sometimes the edges of the others) assume the aspect of basalts.

Gabbro.—Under this term I arrange, as proposed by Professor JUDD, all the coarse-grained granitoid basic rocks of the region without reference to the variety of augite present in them. Under the microscope, they are found to be holocrystalline, but with a granitic rather than an ophitic structure, though traces of the latter are by no means rare. To the naked eye their component minerals are usually recognisable. Professor ZIRKEL, from his examination of the Mull gabbros, believed them to consist of three parts of plagioclase, two parts of olivine, and one part of diallage.* Olivine, however, is not invariably present.† The pyroxene also does not always show the peculiar fibrous structure of diallage. Professor JUDD, indeed, maintains that the diallagic form is due to a deep-seated process of alteration (schillerization), and that the same crystal may consist partly of ordinary augite and partly of diallage.‡ Ilmenite (with leucoxene), magnetite, apatite, biotite, and epidote are not infrequent constituents.

Troctolite (*Forellenstein*).—This beautiful variety of plagioclase-olivine rock occurs as a conspicuous feature on the east side of the gabbro-boss of the island of Rum. It forms a bed on the side of the mountain Allival, in which the component minerals are drawn

* *Zeitschr. Deutsch. Geol. Gesellsch.*, xxiii. (1871), p. 59.

† Professor JUDD (*Quart. Jour. Geol. Soc.*, xlii. p. 62) believes that originally all the gabbros contained olivine, and that where it is now absent, it has been altered into magnetite or serpentine.

‡ *Op. cit.*, xli. In a later paper he insists on the gradation of the coarse granitoid varieties (gabbros) into holocrystalline compounds, where the felspar appears in lath-shapes with crystals or rounded grains of augite and olivine (dolerites), and thence into true basalts, magma-basalts, and tachylytes (*op. cit.*, xlii. p. 62).

out parallel with the upper and under surfaces of the bed. So marked is this flow-structure that hand-specimens might readily be taken at the first glance for ancient schistose limestone. "The felspathic ingredient (probably labradorite or anorthite) is white, and its lath-shaped crystals have ranged themselves with their long axes parallel to the line of flow. The olivine occurs in perfectly fresh grains, which in hand-specimens have a delicate green tint. Under the microscope they appear colourless, and are penetrated by the felspar prisms in ophitic intergrowth. There is a small quantity of a pale brownish augite, which not only occurs in wedge-shaped portions between the felspars, but also as a narrow zone round the olivines." * Considerable differences are visible in the development of the flow-structure, and with these there appear to be accompanying variations in the microscopic structure. Dr HATCH to whom I submitted my specimens, informs me that in one of them, where the flow-structure is so marked as to give a finely schistose aspect to the rock, "there is a larger proportion of augite, some of which exhibits a distinct diallagic striping; the olivine grains show no ophitic structure, but are sometimes completely imbedded in the augite." To this remarkable flow-structure I shall again refer in connection with the light it throws on the bedded character of the exterior of the gabbro bosses.

Between these different basic igneous rocks of the Inner Hebrides, as Professor JUDD has shown, there are many gradations according to the varying proportions of the chief component minerals. Thus from the olivine-gabbros, by the diminution or disappearance of the augite we get such rocks as troctolite; where the plagioclase diminishes or vanishes, we have the different forms of picrite; where the olivine is left out, we come to compounds, like eucrite; while by the lessening or disappearance of the felspar and augite, we are led to ultra basic compounds, consisting in greatest part of olivine like lherzolite and dunite.

§ 2. RELATIONS TO THE OTHER VOLCANIC ROCKS.

Various opinions have been expressed regarding the connection between the amorphous eruptive rocks of the hill-groups and the level basalt-sheets of the plateaux. JAMESON, though he landed at Rudh' an Dunain, in Skye, where this connection can readily be found, does not seem to have made any attempt to ascertain it. He noticed that the lower grounds were formed of basalt, and that the mountains "appeared to be wholly composed of syenite and hornblende rock, traversed by basalt veins." † MACCULLOCH, in many passages of his *Western Islands*, alludes to the subject as one which he knew would interest geologists, but about which he felt that he could give no satisfactory information, and with characteristic verbiage he refers to the impossibility of determining boundaries, to the transition from one rock into another, to the inaccessible nature of the ground, to the almost insuperable obstacles that impede examination, to the distance from human habita-

* MS. of Dr HATCH.

† *Mineralogical Travels* (1813), vol. ii. p. 72.

tion, and to the stormy climate,—a formidable list of barriers, in presence of which he leaves the relative position and age of the rocks unsettled.*

Von Oyenhausen and Von Dechen, who wrote so excellent an account of their visit to Skye, and who traced much of the boundary-line between the gabbros and the other massive eruptive rocks (syenite), seem to have made no attempt to work out the connection between the former and the rest of the volcanic rocks.†

Principal Forbes, in his able sketch of the *Topography and Geology of the Cuchullin Hills*, appears to have been the first to recognise the superposition of the "hypersthene rock" upon the "common trap rocks"—that is, the plateau-basalts. He was disposed to consider the "hypersthene mass as a vast bed, thinning out both ways, and inclined at a moderate angle towards the S.E." ‡

Professor Judd regarded the bosses of basic and acid rocks that rise out of the bedded basalts as the basal cores of enormously denuded volcanic cones. He believed the granitoid rocks to have been first erupted, and that after a long interval the basic masses were forced through them, partly consolidating underneath and partly appearing at the surface as the plateau-basalts.§ That the order of appearance of the several rocks has been exactly the reverse of this supposed sequence will, I think, be fully established in the present memoir. Professor Zirkel recognised that the gabbros are a dependence of the basalts, that they overlie them, and that on the naked flanks of the mountains they are regularly bedded with them. ||

So far as I can learn, however, no one has yet traced out in more detail the actual boundaries of the several rocks on the ground, so as to obtain evidence of their true relations to each other as regards structure and age. Some of the numerous impediments recorded by Macculloch have no doubt retarded the investigation. But, as Forbes so well pointed out, there is really no serious difficulty in determining the true structural connection of the amorphous rocks with each other and with the bedded basalts of the plateaux. I have ascertained them in each of the districts,¶ and as the result of my examination I may briefly state here that there cannot be the least doubt

* See his *Western Islands*, vol. i. pp. 368, 374, 385, 386. With much admiration for the insight and zeal, amounting almost to genius, which Macculloch displayed in his work among the Western Islands, at a time when, with poor maps and inadequate means of locomotion, geological surveying was a more difficult task than it is now, I have found it impossible to follow in his footsteps with his descriptions in hand, and not to wish that for his own fame he had been content to claim credit only for what he had seen. His actual achievements were enough to make the reputation of half-a-dozen good geologists. It was unfortunate that he did not realise how inexhaustible nature is, how impossible it is for one man to see and understand every fact even in the little corner of nature which he may claim to have explored. He seems to have had a morbid fear lest any one should afterwards discover something he had missed; he writes as if with the object of dissuading men from travelling over his ground, and he indeed tacitly lays claim to any thing they may ascertain by averring that those who may follow him "will find a great deal that is not here described, although little that has not been examined" (p. 373). Principal Forbes long ago exposed this weak side of Macculloch and his work (*Edin. New Phil. Jour.*, xl. (1846) p. 82).

† Karsten's *Archiv*, i. p. 99. They frankly admit that "the relation of the hypersthene-rock to the other trap rocks was not ascertained."

‡ *Edin. New Phil. Jour.*, xl. (1846) pp. 85, 86.

§ *Quart. Jour. Geol. Soc.*, xxx. (1874) p. 249.

|| *Zeitschrift. Deutsch. Geol. Gesellsch.*, xxiii. (1871) pp. 58, 92.

¶ In two of my excursions in Mull, and once in Skye, I was accompanied by my colleague Mr H. M. Cadell, and I gladly acknowledge the great assistance he rendered me in mapping those regions.

that the amorphous bosses, both basic and acid, are younger than the surrounding bedded basalts, and that the acid protrusions are on the whole younger than the basic. I shall now proceed to show how these conclusions are established by the evidence of each of the areas where the several kinds of rock occur.

(*a*) *Skye.*—By far the largest, most picturesque, and to the geologist most important area of gabbro in Britain, is that of Skye. Though like every other portion of the volcanic region, it has suffered enormous denudation, and has thereby been trenched to the very core, it reveals, far more conspicuously and clearly than can be seen anywhere else, the relation of the gabbro to the bedded basalts on the one hand, and to the acid protrusions on the other. Its chief portion is that which rises into the group of the Cuillin Hills, which for blackness of hue, ruggedness of surface, jaggedness of crest, and general grimness of aspect, have certainly no rivals within the limits of the British Isles. It has long been known to extend eastwards into Blath Bheinn (Blaven) and its immediate northern neighbours. There is, indeed, no break whatever between the rock of the Cuillins and that of the hills on the east side of Strath na Creitheach. In Strath More the gabbro is interrupted by the granitoid mass of the Red Hills. Patches of it, however, occur further to the east, even as far as the Sound of Scalpa. If we throw out of account the invading granitoid rocks, and look upon the whole tract within which the gabbro occurs as originally one connected area, we find that it covered an elliptical space measuring about nine miles from S.W. to N.E. and six miles from N.W. to S.E., and embracing at least forty square miles.* But that its original size was greater is strikingly shown more particularly on the western margin, which like that of the basalt-escarpments, has obviously been determined by denudation, for its separate beds present their truncated ends to the horizon all along the flanks of the Cuillins, from the head of Glen Brittle round to Loch Scavaig (fig. 36).

The first point to be ascertained in regard to the gabbro and its associated basic rocks of the mountainous tract is their connection in geological structure and age with the bedded basalts of the plateau. This initial and fundamental relation, as FORBES long ago said, can be examined along the whole western and southern flank of the Cuillin Hills, from the foot of Glen Sligachan round to the mouth of Loch Scavaig. Even from a distance, the observer, who is favoured with clear weather, can readily trace the almost level sheets of basalt till they dip gently under the darker rock of the hills. Tourists, who approach Skye by way of Loch Coruisk, have an opportunity, as the steamer nears the island of Soay, of following with the eye the basalt-terraces of the promontory of Rudh' an Dunain until they disappear under the gabbro of the last spur of the Cuillins that guards the western entrance to Loch Scavaig.

What is so evident at a distance becomes still more striking when viewed from nearer ground. Nowhere can it be more impressively seen than at the head of Glen Brittle. Looking westwards, the traveller sees in front of him only the familiar level terraces and

* Though this and the other bosses are here spoken of as consisting of gabbro, it will be understood that this rock only constitutes the larger portion of their mass, which includes also dolerites, basalts, and other basic compounds.

green slopes of the basalt-plateau, rising platform above platform to a height of nearly 1500 feet above the sea. But turning to the east, he beholds the dark, gloomy, cauldron-like Corry na Creiche, from which rise some of the ruggedest and loftiest crests of the Cuillins. On the hills that project from either side of this recess and half inclose it, the bedded basalts mount from the bottom of the valley, with their lines of parallel terrace dipping gently inward below the black rugged gabbro that crowns them and sweeps round to form the back or head of the corry. Down the whole length of Glen Brittle the same structure conspicuously governs the topographical features. On the right hand, the ordinary terraced basalts form the slopes; and they rise for some 500 or 600 feet up the eastern side, until they pass under the darker, more rugged, and less distinctly bedded rocks of the mountains (fig. 36). The dip of the whole series is here at a gentle angle toward S.E., or into the main mass of the Cuillin group.

When, however, we proceed to examine the junction between the two rocks we find it to be less simple than it appears. It is not an instance of mere superposition. The gabbro unquestionably overlies the basalts, and is therefore of younger date. But it overlies them, not as they rest on each other, in regular conformable sequence of eruption, but intrusively, as a sill does upon the rocks on which it appears to follow in the unbroken

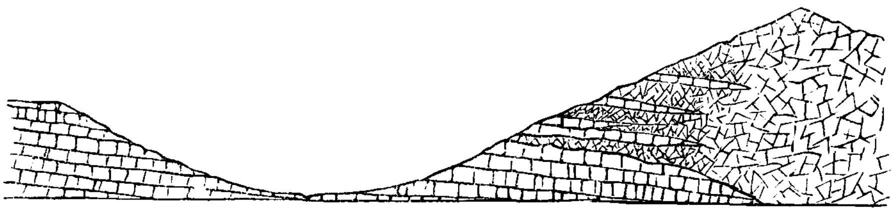


FIG. 36.—Section across Glen Brittle, to show the general relations of the Bedded Basalts (*a*) and the Gabbros (*b*).

order of accumulation. This important structure may be ascertained in almost any of the many sections cut by the torrents which have so deeply trenched with gullies the flanks of the hills. Starting from the ordinary bedded basalts, we observe in mounting the slopes and approaching the gabbro that the rocks insensibly assume that indurated shattery character, which has been referred to as characteristic of them round the margins of vents. Beds of dolerite make their appearance among them, which are so distinctly crystalline, and so resemble in character the rocks of the sills, that there can be little hesitation in regarding them as intrusive. These sills increase in size and number as we ascend, though hardened amygdaloidal basalts may still be observed. True gabbros then supervene in massive beds, and at last we find ourselves entirely within the gabbro area, where, however, thin bands of highly altered basalt still for some distance appear. One further fact will generally be noticed, viz., that before reaching the main mass of gabbro, veins and sills of basalt, as well as of various felsitic and porphyritic members of the acid group, come in abundantly crossing and re-crossing each other in the most intricate network. The base of the thick gabbro-sheets is thus another horizon on which, like that below the plateau-basalts, intrusive masses have been especially developed.

Through all these rocks numerous parallel basalt-dykes, running in a general persistent N.N.W. direction, rise from below the sea-level up even to the very crests of the Cuillins.

The sections on the western side of the area thus prove that the gabbro inosculates with the bedded basalts by sending into them, between their bedding planes, sheets which vary in texture from fine dolerites at the outside into coarse gabbros further towards the central mass, and that this intrusion has been accompanied by a certain amount of induration of the older rocks.

On the eastern side, the same structure can be even more distinctly seen, for it is not only exposed in gullies and steep declivities, but can be traced outward into the basalt-plateau. In the promontory of Strathaird, Jurassic sandstones and shales, which form almost the whole of the coast-line and lower grounds, are surmounted by the bedded basalts. Denudation has cut the plateau into two parts. The smaller of these makes the outlier that rises into Ben Meabost (1128 feet). The larger stretches continuously from Glen Scaladal and Strathaird House northward into Blath Bheinn. Hence from the ordinary terraced basalts, with their amygdaloids, thin tuffs, red partings, and seams of lignite, every step can be followed into the huge gabbro mountain. Starting from the black shales on which the lowest basalt lies, we walk over the successive terraces up into the projecting ridge of An da Bheinn. But as we ascend, sheets of dolerite and gabbro make their appearance between the basalts, which gradually assume the altered aspect already noticed. The dip of the whole series is at a low angle northwards, and the beds can be followed round the head of the Glen nac Leac into the southern slopes of Blath Bheinn. Seen from the eastern side of this valley, the bedded character of that mountain is remarkably distinct, but it becomes less marked towards the upper part of the ridge where the gabbros preponderate. One of the most striking features of the locality is the number and persistence of the N.W. dykes, which strike across from the ordinary unaltered basalts of the plateau up into the highest gabbros of the range. Less durable than the intractable gabbro, they have weathered out where they run up its precipices, thereby causing the vertical rifts and gashes and the deep notches on the crest that form so marked a feature in the scenery. On the other hand, they are often less destructible than the plateau-basalts, and hence in the Glen nac Leac they may be seen projecting as low dams across the stream which throws itself over them in picturesque waterfalls.

The deep dark hollow of the Coire Uaigneich has been cut out of the very core of Blath Bheinn, and lays bare the structure of the east part of the mountain in the most impressive as well as instructive way (Fig. 37). By ascending into this recess from Loch Slapin, we pass over the whole series of rocks, and can examine them in an almost continuous section in the bed of the stream and on the bare rocky slopes on either side. Sandstones and shales of the Jurassic series extend up the Allt na Dunaiche for nearly a mile, much veined with basalt and quartz-porphyry, by which the sandstones are locally indurated into quartzite. At last these strata are overlapped by the basalts of the Strathaird plateau, which with a marked inclination to N.N.W., here dip towards the mountains.

But by the time these rocks have reached this valley, they have already lost their usual brown colour and crumbling surfaces, and have assumed the indurated splintery character, though still showing their amygdaloidal structure. They are much traversed by veins and strings of felsite and quartz-porphyry, which rocks at last appear as a broad band that runs up the bottom of the Coire Uaigneich, and ascending the col, crosses it south-westwards into the Glen nan Leac. On the left or south-eastern side of this intrusive mass, a portion of Lower Silurian quartzite and limestone (here and there altered into white marble) is traceable for several hundred yards up the stream.* Whether this is really in place, and projects as the top of an eminence round and over which the volcanic rocks were accumulated, or whether it is a mass that has been torn away and carried upward during some of the paroxysms of eruption, I could not determine. Knowing how large are the portions of schist embedded between the basalts of Mull, I do not think the great size of this mass necessarily precludes us from regarding it as displaced in the same way. Where the quartzite and limestone first appear at the lower part of the valley, they present an interesting example of that sheared structure with which recent investigations in the North-West Highlands have now made us familiar.† The two rocks have been ground into each other so as to produce a compound that is neither limestone nor quartzite, but a calcareous quartzose schist, in which the beautifully parallel planes of division that mark the surfaces of movement bear the closest resemblance to flow-structure. There can be no doubt that here in the midst of the Tertiary volcanic masses, and not improbably as a result of volcanic explosion, there is revealed to us the existence underneath this district of one of those great thrust-planes in the Silurian rocks which have had so powerful an influence in the production of the younger schists of the Highlands. The evidences of metamorphism and the formation of schists by mechanical movement after the Lower Silurian period, so abundant in the north of Sutherland, are thus found to continue southward even across the island of Skye.

The bedded basalts of Strathaird, after dipping down towards the N.N.W., bend up where they are interbanded with dolerites and gabbros, and form the prominence called An Stac, which rises as the eastern boundary of the Coire Uaigneich. Their steep dip away from the mountain is well seen from the east side, and their outward inclination is continued into the ridge to the southward. Similar rocks appear on the other flank of the band of quartz-porphyry, and form the base of Blath Bheinn. The bedded basalts are everywhere of the usual altered, indurated, and splintery character. The intrusive sheets interposed between them become thicker and more abundant higher up, until they constitute the main mass of the hill. But that they are in separate sheets, and not in one amorphous mass, can be recognised by the parallel lines that mark their boundaries.

The quartz-porphyry sends out veins into the surrounding rocks, and is obviously the youngest protrusion of the locality, except of course the N.N.W. basalt-dykes which

* This limestone was noticed by VON OEYNHAUSEN and VON DECHEN, but they believed it to be a portion of the Lias torn off and carried upward by the eruptive rocks (Karsten's *Archiv*, i. p. 79).

† This rock was first recognised by Mr H. M. CADELL, who accompanied me in one of my excursions over the ground.

cross it, and which are nowhere seen in a more imposing display than round the flanks of Blath Bheinn. A section across the corry shows the structure represented in fig. 37.

It is thus demonstrable that when its line of junction with the surrounding plateau-basalts is traced in some detail, the gabbro is found to overlie them as a whole, but also to be intercalated with them in innumerable beds, bands, or veins which rapidly die out as they recede outwards from the main central mass; that these interposed beds are intrusive sheets or sills proceeding from that mass, and that the contiguous bedded basalts show more or less marked metamorphism. We have now to consider the structure of the interior of the gabbro area of the Cuillin Hills. The first impression of the geologist who visits that wild district is that the main mass of rock is as thoroughly amorphous as a core of granite. Yet a little further examination will reveal to him many varieties of texture, sometimes graduating into, sometimes sharply marked off from, each other, and suggesting that the rock is not the product of one single protrusion. He will recognise further indications of successive discharges or extravasations of crystalline material during probably a protracted period of time, and in the intricate network of veins crossing each other and the general body of the rock in every direction, as well as in

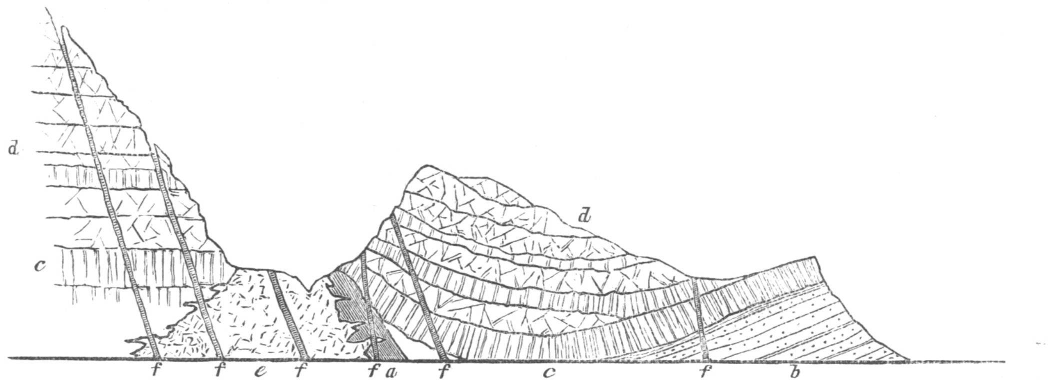


FIG. 37.—Section across the Coire Uaigneich, Skye. *a*, Silurian limestone and quartzite; *b*, Jurassic sandstones and shales; *cc*, bedded basalts and dolerites; *dd*, gabbros and dolerites with indurated basalts; *e*, quartz-porphyry sending veins into surrounding rocks; *ff*, basalt-dykes running north-west through all the other rocks.

the system of steady N.W. basalt-dykes that traverse all the other rocks, he will recognise the completion of the evidence of repeated renewals of subterranean energy.

But he will be struck with the absence of the more usual proofs of volcanic activity in such forms as vesicular lavas and abundant masses of slag, bombs, and tuffs, which are commonly associated with the idea of the centre of a volcanic orifice. Everything around him suggests that he stands, as it were, far beneath that upper part of the earth's crust which is familiar to us in the phenomena of modern volcanoes; that he has been admitted into the heart of one of the deeper layers, where he can study the operations that go on at the very roots of an active vent. He will notice that, on the whole, the rock is largest in grain towards the centre, some features of it around Loch Coruisk reminding him of the most coarsely-crystalline granites. Here and there too, he will observe details of structure that at once recall him to the internal arrangements of the thicker intrusive sheets, but they are displayed here on a still greater scale, as from the bulk of the huge boss of the Cuillin gabbro, might be expected. Portions of the rock show a remarkable segregation or flow-structure, the several minerals being arranged in parallel layers, which sometimes simulate the puckering of true schists. This structure is shown in fig. 38, the light bands consisting mainly of felspar, the darker of the ordinary gabbro, but here and there with the magnetite separated out into distinct lenticular folia. It is singular to find, in the midst of such coarsely crystalline material, exceedingly fine-grained masses of basalt, some of which are amygdaloidal. At the time when I made my last examination of this region, the six-inch Ordnance maps were not issued, and I found it impossible to trace out such details of geological structure on the uncontoured one-inch map, which was the only Ordnance sheet then available. I have every hope, however, that when the mapping of the Cuillin Hills is undertaken on the large scale maps, it will be possible to work out an exceedingly complex structure even in what might be thought to be thoroughly amorphous masses.

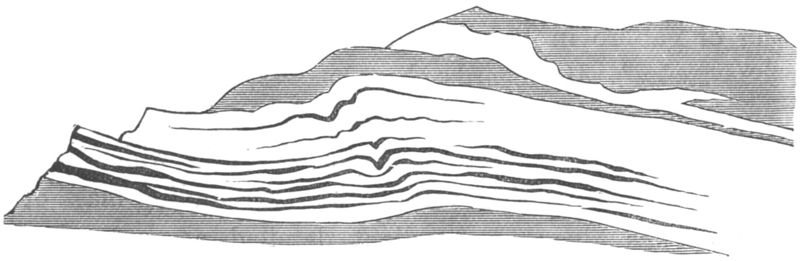


FIG. 38.—Segregation-structure in the Gabbro, from the ridge between Meall Dearg and Loch Coruisk.

There is one important feature which only a minute and patient survey can elucidate, Though I found among the Cuillins no distinct proof that the mass of gabbro ever gave rise to discharges of material, either lava-form or fragmentary, which reached the surface, I obtained unquestionable evidence of explosions and the production of pyroclastic masses. Among the moraine-mounds of Harta Corry, blocks of basalt-agglomerate are strewn about, full of angular fragments of altered basalt, sometimes highly amygdaloidal, and also boulders in which lumps of coarse gabbro are enveloped in a matrix of finer material. But I did not find the parent rocks from which these glacier-borne masses had been derived. That this huge boss of gabbro in Skye, besides invading and altering the bedded basalts, may have communicated eventually with the surface, and have given rise to superficial discharges, is not at all improbable, but of any such outflows not a vestige appears now to remain. We must remember, however, that the gabbro no doubt in many places found its readiest upward ascent in vents belonging to the plateau-period, and that portions of the agglomerates of these earlier vents may be expected to be found involved in it, like that of the great vent of the Red Hills.

Before quitting this area, I will refer to the detached portions of gabbro inclosed in and lying to the east of the mass of the Red Hills. One of the best-marked of these forms a conspicous crag on the east side of Strath More, immediately to the north of Beinn na Cro. It consists of beds of coarse gabbro, with others of dolerite and basalt, and is traversed by veins from the granophyre of the glen, as well as by the usual N.W. basalt dykes (fig. 55). It appears to be a marginal portion of the main gabbro area separated by the intrusion of the great granitoid boss of the Red Hills. On the north-eastern side of Beinn na Caillich numerous intrusive sheets of gabbro and dolerite traverse the quartzite and limestone, and extend down to the sea-margin in the Sound of Scalpa.

(*b*) *Rum.*—The mountains of the island of Rum, rising as they do from a wide expanse of open sea, present one of the most prominent and picturesque outlines in the West Highlands. Less accessible than most of the other parts of the volcanic region, they have been less visited by geologists. They were described by MACCULLOCH as composed of varieties of "augite rock." He noticed in this rock "a tendency to the same obscurely bedded disposition as is observed in other rocks of the trap family," and found at one place that it assumed "a regularly bedded form, being disposed in thin horizontal strata, among which are interposed equally thin beds of a rock resembling basalt in its general characters."* Professor JUDD repeats MACCULLOCH's observation, that "the great masses of gabbro in Rum often exhibit that pseudo-stratfication so often observed in igneous rocks." He regards these masses, like those of Skye and Mull, as representing the core of a volcano from which the superficial discharges have been entirely removed, and he gives a section of the island in which the gabbro is represented as an amorphous boss sending veins into a surrounding mass of granite.† In a more recent paper he has given an excellent detailed account of the mineralogical composition of some of the remarkably varied and beautiful basic rocks constituting the hills of Rum, but adds no further information regarding the geological structure of the island.‡

Even from a distance of eight or ten miles, the hills of Rum are seen to be obviously built up of successive nearly horizontal tiers of rock. As the summer tourist is carried past the island, in that wonderful moving panorama revealed to him by the "swift steamer" of modern days, these great dark cones remind him of colossal pyramids, and as the ever-varying lights and shadows reveal more prominently the alternate nearly level bars of crag and stripes of slope, the resemblance to architectural forms stamps these hills with an individuality which strikes his imagination and fixes itself in his memory. If choice or chance should give him a nearer view of the place, he would not fail to notice that it is among the northern hills of the island that the bedded character is so conspicuous, and that it ceases to be prominent in the southern heights. Crossing over from Eigg, he would recognise each of the features represented in the sketch reproduced in fig. 39. Along the shore, red (Torridon) sandstones rise in naked cliffs, from the top of which the ground seems to slope upward in brown moors to the bare rocky declivities. A deep valley (Glen Dibidil) is seen to

* *Western Islands*, i. p. 486. † *Quart. Jour. Geol. Soc.*, xxx. p. 253.

‡ *Op. cit.*, xli. (1885) p. 354. See also his paper in vol. xlii. of the same Journal.

run into the heart of the hills between the bedded group to the north and the structureless group to the south. If the weather is favourable, some eight or more prominent parallel bars of rock may be counted on the two higher cones to the right. These bars are not quite level, but appear to have a gentle inclination from right to left. They remind one of the terraced basalts of the plateaux, but present a massiveness and a breadth of intervening bare talus-slope such as are not usual among those rocks.

Nor is this impression of regularity and bedded arrangement lessened when we actually climb the slopes of the hills. I had for years been familiar with the outlines of Rum as seen from a distance, and had sketched them from every side, but I shall never forget the surprise and pleasure when my first ascent of the cones revealed to me the meaning of these parallel tiers of rock. I found it to be the structure of the Cuillin Hills repeated, but with some minor differences which are of interest, inasmuch as they enlarge our conceptions of the process by which the gabbro-bosses were formed.

The northern half of the island of Rum consists almost entirely of red sandstone, which is obviously a continuation of the same massive formation so well developed around

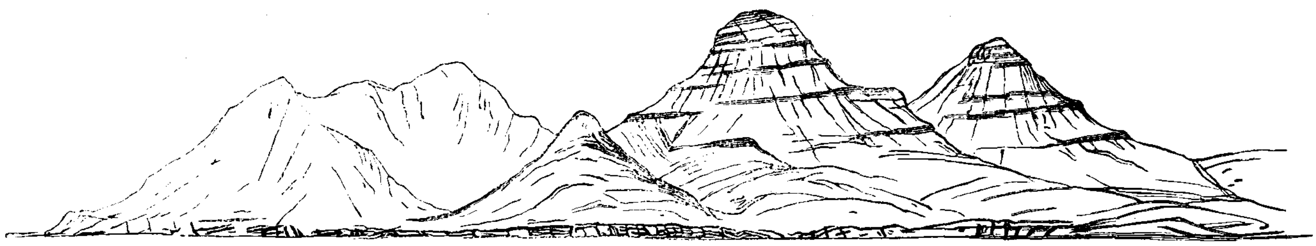


FIG. 39.—Outline of the Hills of the Island of Rum, sketched from near the Isle of Eigg.

Loch Torridon and traceable between the Archæan gneiss and the Lower Silurian strata up as far as Cape Wrath. The sandstones, though full of false bedding, show quite distinctly their true stratification, which is inclined with singular persistence towards W.N.W., at angles averaging from 15° to 20°. If they are not repeated by folds or faults, they must reach in this island a thickness of some 10,000 feet. Their red or rather pinkish tint seems mainly to arise from the pink felspar so abundant in them, for in many places they really consist of a kind of arkose. Pebbly bands with rounded pieces of quartz are of common occurrence throughout the whole formation. Dykes and veins of basalt are profusely abundant. Sometimes these run with the bedding, and might at a distance be taken for dark beds among the pink sandstones. They often also strike obliquely up the face of the cliffs like ribbons.

But, notwithstanding their apparent continuity, there can be no doubt that these sandstones have suffered from those powerful terrestrial disturbances which have affected all the older rocks of the North-West Highlands. On the west side, where they plunge steeply into the sea, they have undergone a change into fine laminated rocks, which might at first be mistaken for shales, but which owe their fissility to shearing movements.

Along their southern border, from a point on the east coast near Bagh-na-h-Uamha, south of Loch Scresort, to the head of Kilmory Glen, they are abruptly truncated against a group of dark, flaggy, and fissile schists and fine quartzites or grits, which in some places are black and massive like basalt, and in others are associated with coarse grey gneiss. That some of these rocks are portions of the Archæan series can hardly be doubted, and the vertical separations and apparent transitions are probably repetitions of the faults and thrust-planes of the north-west. I found also on the northern slopes of Glen Dibidil a patch of much altered grey and white limestone or marble, which reminded me of the Lower Silurian limestone of Skye.

In passing over the zone of these more ancient rocks, we find them to present increasing signs of alteration as they are traced up the slopes towards the great central mass of erupted material. The pink sandstones gradually lose their characteristic tint, and grow much harder and more compact, while the veins and dykes of basalt and sheets of dolerite intersecting them increase in number. The zone of black compact quartzite, which lies to the south of the sandstones, and which at one point reminds us of basalt, at another of the flinty slate of the schistose series, likewise displays increasing induration. Its bedding, not always to be detected, is often vertical and crumpled. But the most remarkable point in its structure is the intercalation in it of bands of breccia. These vary from less than an inch to several yards in diameter; they run mostly with the bedding, but occasionally across it. The stones in them are fragments of the surrounding rock imbedded in a matrix of the same material, but also with pieces of a somewhat coarser grit or quartzite. A band of coarse breccia forms the southern limit of this zone along the northern base of Barkeval and Allival. In general character it resembles the thinner seams of the same material just referred to. The matrix so closely agrees with the black flinty quartzite, that but for the included stones it could hardly be distinguished; so greatly has the mass been indurated that the stones seems to shade off into the rest of the rock. But here and there its true brecciated nature is conspicuously revealed by prominent blocks of hardened sandstone. This band of breccia must in some places be 150 or 200 feet broad. It has no distinct bedding, but seems to lie as a highly inclined bed dipping into the hill. It is at once succeeded by a black flinty felsite like that of Mull. The ground-mass of this rock, so thickly powdered with magnetite grains as to be almost opaque under the microscope, displays good flow-structure round the turbid crystals of orthoclase and the clear granules of quartz. Further up the hill, the rock becomes lighter in colour and less flinty in texture—a change which is found to arise from more complete devitrification, the ground-mass having become a crystalline granular aggregate of quartz and felspar with scattered porphyritic crystals of these minerals (microgranite). In some places, the felsite incloses fragments of other rocks. A specimen of this kind, taken from the head of Coire Dubh, shows under the microscope a brown microfelsitic ground-mass, with crystals of felspar and augite, inclosing a piece of basalt, composed of fine laths of plagioclase, abundant magnetite, and a smaller proportion of granules of augite.

This band of felsite and microgranite may be traced continuously from Loch Gainmich along the base of Barkeval and Allival, and similar rocks appear at intervals along the same line round the eastern base of the hills. Immediately above this belt of felsitic protrusions comes the great body of gabbro. It will be observed that here, as in Skye, the base of the gabbro-mass presents a horizon on which injections of acid rocks have been particularly abundant. If the breccias are not the result of rock-crushings during Palæozoic time, but are really due to volcanic explosions during the Tertiary period, they are evidently older than the eruption of the gabbros. They might be compared with the agglomerate-necks through which the youngest eruptive bosses of Skye have made their way; but in their case the component materials have been derived from the surrounding platform of ancient rocks, and not from subterranean lavas.

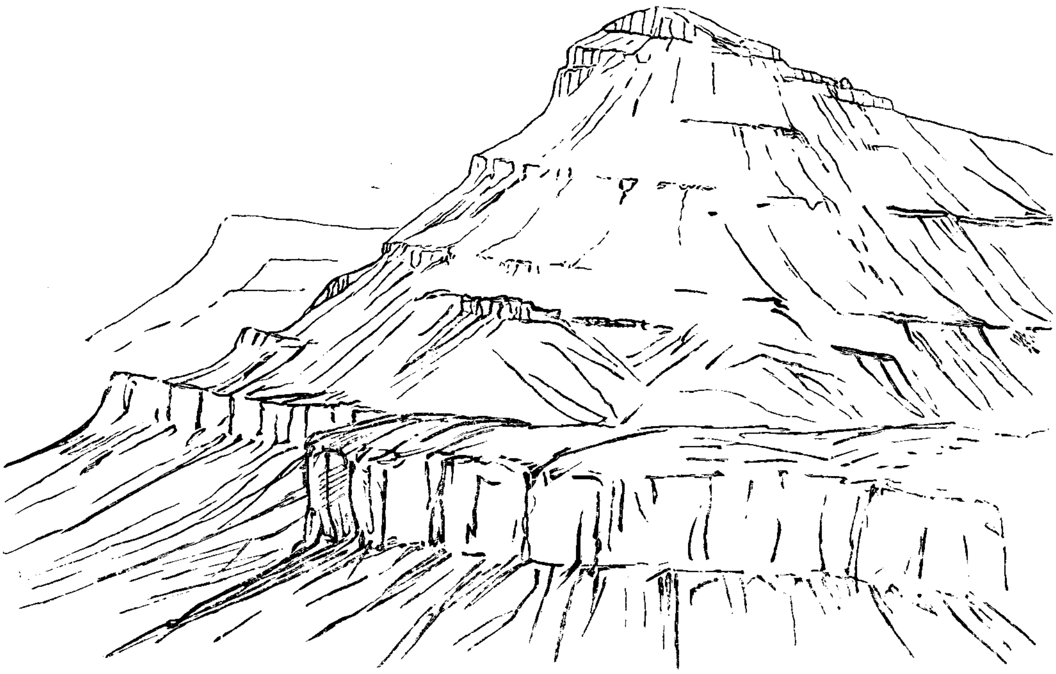


FIG. 40.—View of Allival, Rum, sketched from the base of the north-east side of the cone.

For my present purpose, however, the chief point of importance is the structure of the gabbro mass that springs from that platform into the great conical hills of Rum. The accompanying sketch (fig. 40) will convey a better idea of this structure than a mere description. At the base, immediately above the felsite just referred to, bedded dolerites mark their appearance, much intersected with veins from the siliceous rock. Veins and dykes of basalt also cut all the rocks here, the newest being those which run in a N.W. direction. The lowest beds of dolerite are succeeded by overlying sheets of coarser dolerites, gabbros, troctolites, &c., which are as regular in their thickness and continuity as the ordinary basalts of the plateaux. The band of light-coloured troctolite, in particular, about twenty to thirty feet thick, which has been already referred to, can be followed for some distance along the base of the hill as a marked projecting escarpment (shown in the foreground of fig. 40). Higher up, other varieties are ranged in successive parallel beds, the harder kinds standing out boldly as prominent ribs, while the softer crumble into a kind of sand, which forms talus-slopes between the others. Alternations of this nature are continued up to the very top of the mountain. The beds are nearly flat, but dip slightly into the interior or towards the south-west.

But not only are the gabbro and associated rocks disposed in beds differing from each other in petrographical characters. The same parallel arrangement may be traced even in the internal structure of some of the individual beds. The most remarkable example of this nature which I have found is presented by the band of light-coloured troctolite just referred to. This rock at once arrests attention by its laminar structure. Indeed, hand-specimens of it, as I have said, might readily pass for pieces of schistose limestone. It consists of successive layers, which on the weathered surface divide it into beds almost as regular as those of a sandstone, each bed being further separated into laminæ marked off by the darker and lighter tints of their mineral constituents. The darker layers consist of olivine, and the lighter of plagioclase. This segregation here and there takes the form of rounded masses, where the minerals are more indefinitely gathered together, and the affinity of the rock with intrusive sheets is further displayed by the occurrence of abundant nut-like aggregates of pale green olivine. Examined under the microscope, this flow-structure is admirably seen, the lath-shaped felspars being drawn out parallel to the planes of movement, and giving thereby the peculiarly schistose structure which is so deceptive.

The bedded arrangement of the gabbros is conspicuous from bottom to top of the great eastern cones, as shown in figs. 39 and 40, and the dip is gently inwards to the W. or SW. On the west side also, beyond Loch Sgathaig, a distinct bedding may be traced, the inclination being here once more inwards or to the E. But from Glen Harris and the base of Askival this structure becomes less marked, and gradually disappears. There is thus a central or southern amorphous region, while round the margin towards the north and east the rock appears in frequent alternating beds.

It is clear that in the broad features of their architecture, the hills of Rum follow closely the plan shown in the Cuillin Hills of Skye. In each case, there is a structureless central region, where the rocks are more coarsely crystalline, and an outer marginal belt, where they assume a bedded character and become finer in grain. But, unfortunately, in Rum denudation has gone so far that no connection can be traced on the ground between the gabbros and the plateau-basalts. As already stated, the latter rocks have been almost entirely stripped off from the platform of sandstones and schists which they undoubtedly at one time covered, and the few outliers of them that remain lie at some little distance from the margin of the gabbro area. Nevertheless, we are not without some indications of them underneath the gabbros. I have alluded to the basalts that lie at the base of the eastern cones. As we follow the bottom of the gabbro southward round the flanks of the hills, dull compact black shattery basalts, with a white crust, appear from under the more crystalline sheets. These at once remind one of the altered basalts of Skye and Mull. On the west side also, beds of basalt emerge from under the gabbro, but they have been so veined and indurated by the granophyre of that district, that their relations to the gabbro are somewhat obscured. If we could restore the lost portions of the plateau, I believe we should find the gabbros of Rum resting on part of the volcanic plateau, and some of the gabbro-beds prolonged as intrusive sheets between the beds of basalt.

(*c*) *Ardnamurchan.*—The promontory of Ardnamurchan reveals as clearly as the flanks of the Cuillin Hills, though in a less imposing way, the relations of the gabbros to the plateau-basalts. From the southern shore at Kilchoan to the northern shore at Kilmory, bedded basalts, of the usual type, amygdaloidal and compact, weathering into brown soil, may be followed along the eastern slopes of the hills, resting upon the quartzites and schists of western Argyleshire. These rocks are a continuation of those that cap the ridges further to the south-east and cross Loch Sunart into Morven. They dip westwards, and followed upwards in that direction, they soon present the usual marks of alteration. They weather with a white crust and become indurated and splintery. Sheets of dolerite with many veins and dykes of basalt run between and across them. Bands of gabbro make their appearance, and these, as we advance westwards, increase in number and in coarseness of grain until this rock, in its characteristically amorphous form, constitutes practically the whole of the promontory from Meall nan Con to the lighthouse. Many admirable sections may be seen on the coast-cliffs and in the rugged interior, showing how prone the gabbro in its central structureless portions is to develop segregation-veins. Large crystals of its component minerals run in bands or ribbons across the rock, and traces of a peculiar arrangement may be found to which I shall refer in the following account of the similar rocks of Mull.

(*d*) *Mull.*—In the island of Mull, the conclusions to which the geology of the other volcanic districts leads us as to the position of the gabbros in the series of volcanic phenomena, are confirmed and completed. The first geologist who appears to have observed the relation of these rocks in that island was JAMESON, who classed them under the old name of "greenstone," including in the same designation rocks now termed dolerites and gabbros. He ascended one of the hills above Loch Don, probably Mainnir nam Fiadh (2483 feet), which he found to consist of "strata of basalt and greenstone," with some basalt-breccia or tuff and a capping of basalt. He speaks of the "singular scorified-like aspect" of the weathered greenstone—a description which applies to some of the coarser gabbro bands of that locality. But he appears to have recognised the general bedded arrangement of the rocks up even to the summit of the hill.*

It was not, however, until the visit of Professor ZIRKEL in 1868, that the true petrographical characters of the gabbro of Mull were recognised. The same observer also remarked that the rock is regularly interstratified with the basalt.† Professor JUDD, as already stated, has supposed the gabbros to be the deep-seated portion of the masses

* *Mineralogy of the Scottish Isles*, i. p. 205.

† *Zeitsch. Deutsch. Geol. Gesellsch.*, xxiii. (1871) p. 58.

which when poured out at the surface became the plateau-basalts, and he represents them in his map and sections of Mull as ramifying through the granitic rocks.*

In Mull some peculiarities in the arrangement of the gabbro are better developed than elsewhere. Instead of forming a huge boss with an amorphous centre and a fringe of intrusive sheets, as in Skye and Ardnamurchan, the rock is distributed in innumerable beds or sheets interposed between the plateau-basalts. The area within which this chiefly occurs is tolerably well-defined by the difference of contour between the long terraced uplands of the ordinary basalts and the more conical forms of the southern group of hills between Loch na Keal and Loch Spelve. The number and thickness of the gabbro-sheets increase as we proceed inwards from the basalt-plateau. These sheets are specially prominent along the higher parts of the ridge that runs northwards from the northern end of Loch Spelve, and along the west side of Glen Forsa. But they swell out into the thickest mass in the south-western part of the hilly ground, where from above Craig, in Glenmore, they cross that valley, and form the rugged ridge that rises into Ben Buy (2354 feet), and stretches eastward to near Ardara. It is in this southern mass that the Mull gabbro approaches nearest in general characters to the bosses of the other districts. But even there, its true intercalation above a great mass of bedded basalt may readily be ascertained in any of the numerous ravines and rocky declivities.

One of the best lines of section for exhibiting the relations of the rocks is the declivity to the west of Ben Buy and Loch Fhuaran. Ascending from the west side, we walk over successive low escarpments and terraces of the plateau-basalts with a gentle inclination towards N.E. or E. These rocks weather in the usual way, some into a brown loam, others into spheroidal exfoliating masses. But as we advance uphill, they gradually assume the peculiar indurated shattery character already referred to. The soft earthy amygdaloids become dull splintery rocks, in which the amygdules are no longer sharply defined from the matrix, but rather seem to shade off into it, sometimes with a border of interlacing fibres of epidote. The compact basalts have undergone less change, but they too have become indurated, and generally assume a white or grey crust, and none of them weather out into columnar forms. Strings and threads full of epidote run through much of these altered rocks. Abundant granophyric and felsitic veins traverse them. Sheets of dolerite likewise make their appearance between the basalts, followed further up the slope by sheets of gabbro until the latter form the main body of the hill.

On the north side of the same ridge, similar evidence is obtainable, though somewhat complicated by the injections of granophyric and felsitic veins and bosses, to which more detailed reference will afterwards be made. But the altered basalts, with their amygdaloidal bands and their intercalated basalt tuffs and breccias, can be followed from the bottom of the glen up to a height of some 1700 feet, above which the main gabbro mass of Ben Buy sets in. Many minor sheets of dolerite and gabbro make their appearance along the side of the hill before the chief overlying body of the rock is reached. Some

* *Quart. Jour. Geol. Soc.*, xxx. (1874).

of these can be distinctly seen breaking across or ending off between the bedded basalts which here dip gently into the hill (fig. 41). A conspicuous band of coarse basalt-agglomerate, containing blocks of compact and amygdaloidal basalt a yard or more in diameter, shows by the excessive induration of its dull-green matrix the general alteration which the rocks of the basalt-plateau have here undergone. An almost incredible number of veins of fine basalt, porphyry, and felsite has been injected into these rocks—a structure which is precisely a counterpart of what occurs under the main body of gabbro in Skye, Ardnamurchan, and Rum.

The gabbro mass of the Ben Buy ridge is thus undoubtedly a huge overlying sheet, which probably reaches a thickness of at least 800 feet. It seems to descend rather across the bedding into the hollow of Glen More, and possibly its main pipe of supply lay in that direction. Being enormously thicker than any other sheet in the island, it exhibits the crystalline peculiarities which are so well developed in the central portions of the larger bosses of gabbro. It presents more coarsely crystalline varieties than appear in the thinner sheets, some portions showing crystals of diallage and felspar upwards of

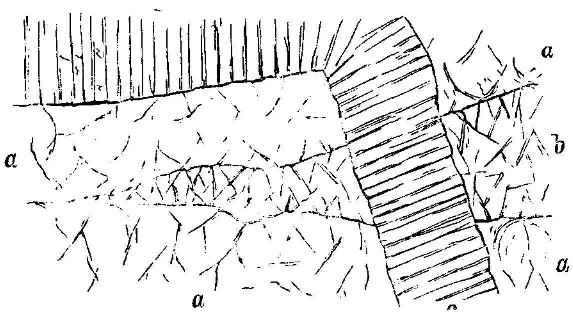


FIG. 41.—Altered Plateau-Basalts invaded by Gabbro, and with a Dyke of prismatic Basalt cutting both rocks, North Slope of Ben Buy, Mull. *aa*, amygdaloidal basalt, much altered; *b*, gabbro; *c*, finely prismatic basalt.

an inch in length. It likewise contains admirable examples of segregation-structure, which, as in Skye and elsewhere, is best developed where the texture becomes especially coarse. These veins or seams, in which the constituent minerals have crystallised out in more definite and conspicuous forms, here and there succeed each other so quickly as to impart a kind of bedded or foliated look to the body of rock in which they occur, recalling the aspect of some coarsely crystalline granitoid gneiss. Occasionally, on the exposed faces of crags, portions of such veins are seen to be detached and enveloped in the finer surrounding matrix. This pseudo-stratification is to be distinguished from another structure in which thick belts or bands of coarser and finer texture alternate, and give an appearance of bedding to the mass. These bands run generally parallel with beds of highly indurated basalt, which appear to be separated portions of the ordinary rocks of the plateau. They may be taken to indicate that the thick sheet of Ben Buy is not the result of one but of many uprises of gabbro.

Of the thinner sheets of dolerite and gabbro little need here be said. I have referred to their great abundance in the range of eastern hills that rise from the Sound of Mull between Loch Spelve and Fishnish Bay. Though obviously intrusive, they lie on the whole parallel to the bedding of the basalts. The latter rocks exhibit the usual dull indurated shattery character which they assume where the gabbro has invaded them, and which gradually disappears as we follow them down hill away from the intrusive sheets to the shores of the Sound. They dip towards the centre of the hill group, that is to S.W. in the ridge of Mainnir nam Fiadh, Dun da Ghaoithe, and Beinn Meadhon, the angle increasing southwards to 15°–20°, and at the south end reaching as much as 35°–40°. Some fine crags of gabbro and dolerite form a prominent spur on the east side of the ridge of Ben Talaidh, in the upper part of Glen Forsa. These consist of successive sheets bedded with the basalts, and dipping S.W. A large sheet stands out conspicuously on the north front of Ben More, lying at the base of the "pale lavas," and immediately above the ordinary basalts, and circles round the fine corry between Ben More and A'Chioch, some of its domes being there beautifully ice-worn. This is the highest platform to which I was able satisfactorily to trace any of the intrusive sheets of Mull. Another dyke-like mass emerges from beneath the talus slopes of A'Chioch, on the southern side, and runs eastward across the col between the Clachaig Glen and Loch Scridain.

§ 3. Structure of the Gabbro Areas.

We are now in a position to draw, from the observations which have here been given regarding the different areas of gabbro in the Tertiary volcanic region of Britain, some general conclusions with respect to the type of geological structure which they illustrate.

1. No evidence exists to show that the extruded masses of gabbro ever communicated directly with the surface. They never exhibit the cellular, slaggy and other structures so characteristic of surface-flows. They are, on the whole, free from included masses of breccia and agglomerate, though portions of such rocks have been detected among the boulders derived from one part of the Cuillin Hills. If the gabbro-bosses ever were continuous with sheets of rock emitted above ground, all such upward continuations have been entirely removed. In any case, we may be quite certain that in an outburst at the surface the rock would not have appeared in the form of a coarsely crystalline or granitoid gabbro.

2. The crystalline structures of the gabbros point unmistakably to slow cooling and consolidation at some considerable depth beneath the surface. The most coarsely-crystalline varieties, and those with the best developed segregation-veins, occur in the largest bodies of rock, where the cooling and consolidation would be most prolonged.*

3. From the occurrence of bands and more irregular portions of considerably different texture and even mineralogical composition, it may be confidently inferred that even what appears now as one continuous mass was produced by more than one eruption.

4. In every case there would necessarily be one or more pipes up which the igneous material rose. These channels might be supplied by wider parts of fissures, such as those filled by the dykes. But more probably they were determined by older vents, which had

* On this subject, see the papers by Professor Judd already cited.

served for the emission of the plateau-basalts and their pyroclastic accompaniments. There can be no doubt that some of these vents afforded egress for the subsequent eruption of granitoid rocks. In the case of the gabbros, however, they seem to have been generally concealed by the tendency of these rocks to spread out laterally. Denudation has cut deeply into the gabbro-masses, but not deep enough to isolate any of the pipes from the material which issued from them, so as to leave solitary necks like those in and around the basalt-plateaux. In Skye, where the central core of gabbro is largest and most completely encircled, we cannot tell how much of it which is amorphous and resembles what might be supposed to be the material filling the actual vent, really lies above the true pipe or pipes, and has spread out on all sides from the centre of eruption. All that we know is that round the margin of the gabbro we can reach horizons below that rock, and see that it lies as a cake or series of cakes upon the plateau-basalts. The actual pipe of supply must lie further inward, away from the margin, and may be of comparatively small diameter.

5. From the central pipe or group of pipes which rose from the platform of older rocks into the thick mass of the basalt-plateaux, successive sheets of dolerite and gabbro were forced outward between the layers of basalt. This took place all round the orifices of supply, on many different horizons, and doubtless at many different times. In some cases, the intrusive sheets were injected into the very bottom of the basalts, and even between these rocks and the older surface on which they rested. This is particularly the case in Rum, where the gabbro-cones spring almost directly from the ancient grits, schists, and sandstones on which they rest. The intrusive sheets have likewise found egress at every higher platform in the basalt-series, up at least to the base of the pale group in Mull—that is, through a continuous pile of more than 2000 feet of bedded basalt. But the intrusion did not proceed equally all round an orifice. At all events, the progress of denudation has revealed that on one side of a gabbro area the injected portions may occur on a lower stratigraphical level than they do on the opposite side. At the Cuillin Hills, for example, the visible sheets of dolerite and gabbro to the north of Coire na Creiche begin about 1600 feet above the sea, which must be much more than that distance above the bottom of the basalts. On the south-east side, however, they come down to the Torridon sandstone at Loch Scavaig; that is to say, their lowest members lie about the base of the bedded basalts, or more than 1600 feet below those on the opposite margin.

6. The uprise of so much igneous material in one or more funnels, and its injection between the beds of plateau-basalt, would necessarily elevate the surface of the ground immediately above, even if we believe that surface to have been eventually disrupted and superficial discharges to have been established. If no disruption took place, then the ground would probably be upraised into a smooth dome, the older lavas being bent up over the cone of injected gabbro until the portion of the plateau so pushed upward had risen some hundreds of feet above the surrounding country. The amount of elevation, which would of course be greatest at the centre of the dome, might be far from equable all round, one

side being pushed up further or with a steeper slope than another side. But even in the case of the Cuillin Hill area, it is conceivable that the total uplift produced at the surface a gentle inclination of no more than 8° or 10°.

It is along the periphery of a gabbro area that we may most hopefully search for traces of this uplift. But unfortunately it is just there that the work of denudation has been most destructive. Thère appears also to have been a general tendency to sagging subsequent to the gabbro protrusions, and the inward dip thereby produced has probably been instrumental in effacing at least the more gentle outward inclinations caused by the uprise of the eruptive rock. In one striking locality, however, to which I have already referred, the effects of both movements are, I think, preserved. The basalt-plateau of Strathaird, which in its southern portion exhibits the ordinary nearly level bedding, dips in its northern part at an unusually steep angle to the N.W., towards the gabbro mass of Blath Bheinn. But before reaching that mountain the basalts, much interbanded with sheets of dolerite and gabbro, suddenly bend up to form the prominent eminence of

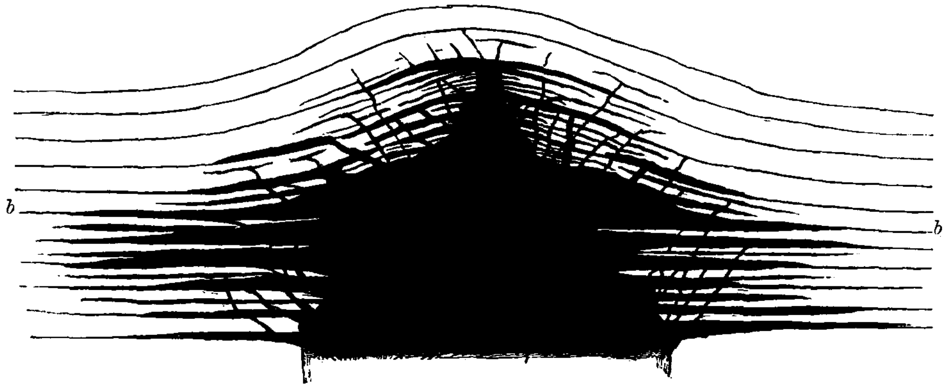


FIG. 42.—Theoretical representation of the structure of one of the Gabbro Bosses of the Inner Hebrides. *a*, platform of older rock on which the bedded basalts (*b*) have been poured out; *c*, gabbro.

An Stac, where they dip rapidly towards S.E. and S. (fig. 37). This steep dip away from the central mass of gabbro, is repeated in the hills to the north, where the beds are inclined to N.E., the angle gradually lessening northwards till they are truncated by the granophyre of Strathmore. The theoretical structure of one of the gabbro bosses is represented in fig. 42.

7. The injection of so much igneous material among the bedded basalts has induced in these rocks a certain amount of contact metamorphism. I have referred to it as showing itself in the field as a marked induration, the rocks becoming closer grained, dull, and splintery, weathering with a grey or white crust, while their amygdules lose their definite outlines, and epidote and calcite run in strings, veins, and patches through many parts of the rocks.* The microscopic characters of the altered basalts are described at p.167.

* Many years ago I was much struck with the evidence of alteration in the igneous rocks of Mull, and referred to it in several papers, *Proc. Roy. Soc. Edin.* (1866–67), vol. vi. p. 73; *Quart. Jour. Geol. Soc.*, xxvii. (1871) p. 282, note.

The structure and history of the gabbro bosses of the Inner Hebrides find a close parallel in those of the Henry Mountains of Southern Utah, so well described by Mr G. K. GILBERT of the United States Geological Survey. In that fine group of mountains, rising to an extreme height of 5000 feet above the surrounding plateau, and 11,000 feet above the level of the sea, masses of trachyte have been injected between sedimentary strata belonging to the Jura-Triassic and Cretaceous systems. These masses, thirty-six in number, have consolidated in dome-shaped bodies, termed by Mr GILBERT "laccolites," which have arched up the overlying strata, sending sheets, veins, and dykes into them, and producing in them the phenomena of contact metamorphism. There is no proof that any of these protrusions communicated with the surface, and there is positive evidence that most if not all of them did not. The progress of denudation has laid bare the inner structure of this remarkable type of hill, and yet has left records of every stage in its sculpture. In one place, are seen only arching strata, the process of erosion not having yet cut down through the dome of stratified rocks into the trachyte that was the cause of their uprise. In another place, a few dykes pierce the arch; in a third, where a greater depth has been bared away, a network of dykes and sheets is revealed; in a fourth, the surface of the underlying "laccolite" is exposed; in a fifth, the laccolite, long uncovered, has been carved into picturesque contours by the weather, and its original form is more or less concealed.*

The gabbro "laccolites" of the west of Scotland belong to an older geological period than those of Utah, and have, therefore, been longer subject to the processes of denudation. They have been enormously eroded. The overlying cover of basalt has been stripped off from them, though from the escarpments beyond them it is not difficult in imagination to restore it. In Rum it has been so completely removed, that only a few fragments remain at some distance from the cone of gabbro which now stands isolated. In Ardnamurchan, and still more in Skye, the surrounding plateau of basalt remains in contact with the gabbro bosses. But in Mull, where the plateau basalts reach now, and perhaps attained originally a greater thickness than anywhere else, they have protected the intrusive sheets, which are less deeply cut away there than in any of the other districts, and no great central core of gabbro has yet been uncovered.

IV. THE ACID ROCKS.

We now come to the consideration of the last and in some respects the most singular phase of volcanic action during Tertiary time in Britain. Hitherto all the igneous rocks that have been under consideration in this memoir, whether injected below or poured out at the surface, have been of basic, some of them indeed, like the peridotites, of ultra-basic character. But we now encounter a great series, every member of which is more or less decidedly acid, and in which the excess of silica is very commonly visible to the

* "Geology of the Henry Mountains," by G. K. Gilbert, *U. S. Geographical and Geological Survey of the Rocky Mountain Region*, 1877.

eye in the form of free quartz. While in chemical composition there is the strongest contrast between this series and the rocks hitherto under discussion, there are also marked differences in structure and mode of occurrence. With one solitary exception (Scuir of Eigg), all the masses of acid rock are intrusive—that is, they have been injected beneath the surface, and therefore record for us subterranean and not superficial manifestations of volcanic action.

The existence of rocks of this class in the midst of the basic masses has long been recognised. They were noticed by JAMESON, who described the hills between Loch Sligachan and Broadford as composed of "a compound of felspar and quartz, or what may be called a granitel, with occasional veins of pitchstone."* MACCULLOCH gave a fuller account of the same region, and classed the rocks as chiefly "syenite" and "porphyry."† In Antrim, also, even in the midst of the basalt-tableland, masses of "pitchstone-porphyry," "pearlstone-porphyry," and "clay-porphyry" were observed and described.‡ In more recent years Professor ZIRKEL has given a brief account of the so-called "syenite and porphyry" of Mull and Skye§ and the late Professor VON LASAULX fully described the trachyte of Antrim, in which he recognised the occurrence of tridymite.||

It is remarkable that up to the present time no connected account of the petrography or of the geological relations of this interesting series of rocks has been published. Yet we find in it a greater variety of petrographical characters than in any other portion of the British Tertiary volcanic rocks. On the one hand, it presents us with thoroughly vitreous masses, some of which in their colour, lustre, and microscopic structure remind us of recent obsidians. On the other hand, it affords us coarsely crystalline compounds, to which we can assign no other name than granite, and which, did we not know their geological position, we might class with some of the most ancient eruptive rocks. Between these two extremes abundant gradations may be found.

In dealing with such a series of intrusive rocks, we again encounter the difficulty of reaching certainty as to their relative dates of eruption, since in each case all that can usually be affirmed is that the intrusive mass is younger than that into which it is injected. It is quite possible that protrusions of acid rocks occurred at many intervals during the accumulation of the basic masses. We have already seen that in gravels near the base of the basalt-plateau of Mull, and in the agglomerates of that island as well as of other districts, fragments of siliceous lavas occur. It is quite certain, therefore, that at the time when the basalts of the plateaux were emitted, there existed, within reach of volcanic explosions, masses of felsitic rocks, fragments from which were shot up the funnels of discharge. Whether portions of these rocks were actually intruded into the basalt-sheets before the building up of the plateaux was completed, or whether in some cases the molten material was poured out in streams of lava at the

* *Mineralogical Travels*, ii. 90.

† *Western Isles*, see the descriptions of Skye, Mull, and Rum.

‡ Berger, *Trans. Geol. Soc.*, iii. (1816) p. 190.

§ *Zeitsch. Deutsch. Geol. Gesellsch.*, xxiii. (1871) pp. 54, 77, 84, 88.

|| Tschermak's *Min. und Petrog. Mittheilungen*, 1878, p. 412.

surface, cannot be decided from the evidence which I have as yet been able to gather. All I can affirm at present is—(1) that in no single instance have I met with a trace of any acid lava that reached the surface save that of the Scuir of Eigg, which belongs to a period long subsequent to the formation of the basalt-plateaux; and (2) that where the relative ages of the rocks can be fixed, the acid protrusions are almost invariably the youngest. Indeed, the only exceptions to this rule are the latest basalt-dykes and possibly a few basic injections along the margins of the larger gabbro areas. Hence, while I frankly admit that the large and varied series of acid rocks, which no doubt represents a wide interval of time, may in part belong to comparatively early epochs in the protracted volcanic period, the actual available evidence places the emission of these rocks as a whole towards the end of the volcanic history. This evidence I shall bring forward in full detail, since it necessitates an abandonment of what up to the present has been the general belief in regard to the relative ages of the rocks.

§ 1. Petrography.

The classification of the rocks which best harmonises the field-evidence and the detailed study of their mineralogical composition, is one which arranges these volcanic protrusions into two series. In the first, the orthoclase is sanidine, and the rocks range from the most vitreous pitchstone through perlitic and spherulitic varieties to quartz-trachyte. In the second series, which embraces by far the largest proportion of the whole, the orthoclase is always turbid, and in this respect as well as in many others the rocks remind us rather of ancient eruptive masses than of those which have appeared in Tertiary time. They range from flinty felsitic varieties, which are obviously devitrified glasses through different textures of quartz-porphyry into granophyre, and finally into granite. As I have been unable to recognise any essential difference of structure and composition between these acid Tertiary rocks and those of far earlier geological time, I give them the names which no petrographer would hesitate to apply to them if they were of Palæozoic age. It has long appeared to me that these rocks furnish conclusive evidence of the misleading artificiality of any petrographical nomenclature in which relative antiquity is made an essential element of discrimination.

1. *Pitchstone and Trachyte Series.*

These rocks, though distributed over a tolerably wide area, never occur in the large masses characteristic of the felsitic and granophyric series. They almost always appear as veins, and usually in the vitreous condition, the only exceptions yet known being the bosses of trachyte which rise here and there through the Antrim basalt-plateau.

Pitchstone.—This rock is found in veins or dykes which rise through different geological formations up to and including the great granophyre bosses of the Inner Hebrides. It also in one solitary example occurs as a lava-stream, or rather a succession of streams, piled over each other in the ancient river-bed of the Scuir of Eigg. It varies in colour from a deep jet-black or raven-black to a pale bottle-green, and in lustre from an almost glassy obsidian-like to a dull resinous aspect. Occasionally it assumes a dull felsitic texture, owing to devitrification, and also a finely spherulitic structure. Some varieties appear to the naked eye to be perfectly homogeneous, others become porphyritic by the appearance of abundant sanidine crystals.

The microscopic structure of the British pitchstones has only been partially worked out. The beautiful feathery microlites of the Arran dykes, first made known by DAVID FORBES, and subsequently described by ZIRKEL, ALLPORT, and others, are well known objects to geological collectors. But no one has yet attempted to investigate the group as a whole. I have placed my tolerably large collection of specimens and their slides in the hands of Dr HATCH, from whom we may expect before long a memoir on this interesting and still little known group of rocks. In the meantime, he has furnished me with some preliminary notes on the slides, from which I make the following generalised summary.

At the one end of the pitchstone group we have a nearly pure glass, with no microlites, and only a few scattered crystals of sanidine, quartz, augite, or magnetite. The glass in thin slices is almost colourless, but generally inclines to yellow, sometimes to dark-grey. Some varieties of the rock are crowded with microlites, in others these bodies are gathered into groups, the glass between which is nearly free from them. Among the minerals that have been observed in this microlitic form are sanidine, augite, hornblende (forming the beautiful green feathery or fern-like aggregates in the Arran pitchstones), and magnetite. Sometimes the rudimentary forms appear as globulites or as belonites, but more commonly as dark trichites. Among the more definite mineral forms are grains of sanidine, quartz, and augite. The porphyritic crystals are chiefly sanidine, augite, and magnetite, but plagioclase occasionally occurs. The development of spherulites is well seen in a few of the slides, and occasionally perlitic structure makes its appearance. At the Scuir of Eigg, bands of a dull felsitic pitchstone occur, which under the microscope show that the glass has been so devitrified as to assume a cryptocrystalline structure.

Quartz-Trachyte.—This rock has not yet been noticed in any other district than in Antrim, where it rises in occasional bosses among the plateau-basalts. It is best exposed at the Tardree and Carnearny Hills, where it has long been quarried. Its petrographical characters were fully described by VON LASAULX, who found the rock to be a typical quartz-trachyte rich in tridymite, and containing large crystals of glassy sanidine, isolated narrow laths of plagioclase (probaby andesine), grains of smoky-grey quartz, partly bounded by di-hexahedral faces, and a few scattered flakes of a dark-coloured mica. The ground mass is microgranitic, and under a high power is resolvable into a confused aggregate of minute microlites of felspar, with interstitial quartz-granules.*

* Tschermak's *Min. und Pet. Mittheil.*, 1878, p. 412.

2. *Felsite, Quartz-Porphyry, Granophyre, and Granite Series.*

Felsite and Quartz-Porphyry.—Under the general name of felsite, I class an abundant group of rocks, which macroscopically vary in texture from flinty or horny to dull finely granular, and in colour from white through shades of grey, buff, and lilac, to black, generally with porphyritic felspars and blebs of quartz. Where these porphyritic enclosures increase in size and number, the rocks cannot be distinguished from ancient quartz-porphyries, and I have preferred to call them by that name.

In no single instance have I found any vitreous variety among them, nor any remnant of true glass in their minute structure. But that many, if not all of them, were originally glasses can hardly be doubted. They often exhibit the most beautiful flow-structure, the laminæ being distinctly visible to the naked eye as they curve round the porphyritic crystals of earlier consolidation. Sometimes indeed this structure has been so strongly developed as to cause the rock to weather along the planes of flow and to break up into thin slabs. The passage of the original glass into a lithoid condition does not seem to have been accompanied with the development of those well-marked types of microlites so characteristic of the pitchstones. On the contrary, I have never detected any other modification than that confused and indefinite aggregate which is known as felsitic. Occasionally a spherulitic structure may be observed. More frequently the peculiar radially-fibrous aggregation of quartz and felspar presents itself, which is the characteristic structure of the granophyres. There is thus a gradation from ordinary felsites and quartz-porphyries through granophyric varieties into perfect granophyres.

The felsites and quartz-porphyries present many of the structures of rhyolites, and would in fact be classed by many petrographers under that name. But I think it better to keep the term rhyolite for those acid lavas wherein the felspar occurs as crystals of sanidine, which, together with quartz, are embedded in a microcrystalline felsitic or vitreous ground-mass.

There is here again an obvious relation between lithological texture and geological position. Where the acid rocks have been injected into narrow chinks and fissures, they are finer in grain than in the centre of large masses, and have generally consolidated as veins or dykes of felsite or quartz-porphyry. Where they have accumulated in larger bosses, as in Mull and Skye, they have taken the form of granophyres or granites. Along the margins of these bosses, where the conditions of cooling and crystallisation more nearly resembled those in the fissures, the rocks are finer in texture, and not unfrequently assume the felsitic or porphyritic aspect, and even show a more or less perfect flow-structure.

Granophyre.—This term, which is here used in the sense employed by ROSENBUSCH (but without his limitation of it to pre-Tertiary rocks), embraces undoubtedly the most characteristic and abundant rocks among the acid protrusions of the Inner Hebrides. These vary in texture from a fine felsitic or crystalline-granular quartz-porphyry, in the ground-mass of which porphyritic turbid felspar and quartz (sometimes bi-pyramidal) may generally be detected, to a granitoid rock of medium grain, in which the component dull felspar and clear quartz can be readily distinguished by the naked eye. Throughout all the varieties of texture there is a strong tendency to the development of minute irregularly-shaped cavities, which here and there give a carious aspect to the rock. That these cavities, however, are part of the original structure of the rock, and are not due to mere weathering, is shown by the well-terminated crystals of quartz and felspar which project into them. On a small scale, it is the same structure so characteristic of the granite of the Mourne Mountains and of parts of that of Arran.

Examined under the microscope, a normal specimen of the granophyre of the Western Isles presents a holocrystalline ground-mass, which fills all the interspaces between the crystals of earlier consolidation. This ground-mass consists of an aggregate of clear quartz and turbid orthoclase, arranged in the structure known as micropegmatite. In some parts these two minerals are grouped in alternate parallel fibres, diverging from the surface of the enclosed crystals, which are thus more or less completely surrounded by a radially fibrous mass. In other parts, the felspar forms a kind of network, the meshes of which are filled up with quartz. Through the ground-mass are scattered crystals of clear quartz and dull orthoclase, generally with some ferro-magnesian or other additional constituent, usually somewhat decomposed. In some varieties Dr HATCH has found an abundant brown mica, as in the rock at Camas Malag, Skye. In others, a pyroxene occurs, which he finds in minute greenish grains, sometimes completely inclosed in the quartz. In a third variety the dark constituent is hornblende, the most remarkable example of which is one to be seen at Ishriff, in the Glen More of Mull, where the ferro-magnesian mineral takes the form of long dirty-green needles, conspicuous on a weathered surface of the rock. A fourth variety is distinguished by containing plagioclase in addition to or instead of orthoclase. In the rock of the sheet forming Cnoc Carnach, near Heast, in Skye, Dr HATCH has observed both orthoclase and plagioclase scattered through a fine micro-pegmatitic ground-mass, and in a part of the boss at Ishriff he has found the rock to be composed mainly of plagioclase, in a micropegmatitic ground-mass of quartz and felspar, with a few scattered grains of a pale brown augite and grains of magnetite. A fifth variety is marked by the prominence of the crystals of quartz and felspar of earlier consolidation, and the fineness of grain in the surrounding micropegmatitic ground-mass, whereby a distinct porphyritic structure is developed. Rocks of this kind are macro-scopically like ordinary quartz-porphyries.

The granophyres occur sparingly as veins or dykes. Conspicuous examples of their assumption of this form are to be seen in the light-grey veins which break through the dark gabbro at the lower end of Loch Coruisk, Skye. More massive and striking are the great dykes that run up the basalt-terraces on the north side of Loch Sligachan. In the form of sheets intruded between the Jurassic strata, or between them and the base of some overlying series now removed, the granophyres (having the general aspect of quartz-porphyries) play an important part in the geology of Strath, in Skye. But it is as bosses that the granophyres attain their largest and most characteristic development, their greatest area being in the groups of the Red Hills of Skye, between Loch Sligachan and Strath.

Microgranite.—This name is applied to certain intrusive masses, which macroscopically may be classed with the quartz-porphyries and felsites, but which microscopically are found to possess a holocrystalline granitic ground-mass of quartz and orthoclase, through which are scattered porphyritic crystals of the same two minerals, sometimes also with plagioclase, augite, magnetite, or apatite. Rocks of this type do not appear to be abundant. They occur as dykes and bosses, but occasionally also as sheets. I have collected them from Skye, Rum, and Ardnamurchan.

Granite.—That there are true granites among the acid rocks of the Tertiary volcanic series can no longer be doubted. As in their macroscopic characters the more coarsely crystalline granophyres are not to be distinguished from granites, and, as their dark ferro-magnesian constituent is generally hornblende, they were called by the older petrographers "syenite"; that is, granite with hornblende instead of mica. In many of the granophyres, the microscope reveals transitional stages to granite. The peculiar micropegmatitic ground-mass may be observed so reduced in amount as only to appear here and there between the other minerals which are grouped in a granitic structure. From this condition, one step further carries us into a true granite, from which all trace of the granophyric character has disappeared. Such gradations may be traced even within short distances in the same boss of rock. Thus, portions of the interior of the boss of Beinn-an-Dubhaich, Skye, possess a thoroughly granitic arrangement of their component minerals, while a specimen taken from near the edge on the shore of Camas Malag, shows the appearance of the granophyric ground-mass. But, though the large bosses are usually somewhat coarsely crystalline in the centre, and tend to assume finer felsitic textures around their borders, as was observed long ago by OEYNHAUSEN and VON DECHEN,* the granitic structure is sometimes exhibited even at the very edge, and not only so, but in the dykes that protrude from the bosses into the surrounding rocks. Thus the Beinn-an-Dubhaich mass, at its margin on Camas Malag, sends a vein into the surrounding limestone, but though more close-grained than the main body of the rock, this vein is neither felsitic nor granophyric, but truly granitic in structure.

So far as I have observed, the true granites contain a brown mica and also a little hornblende, both visible to the naked eye, but generally somewhat decomposed. These rocks are thus hornblende-biotite-granites (amphibole-granitites of ROSENBUSCH). They may be defined as medium-grained aggregates of quartz, orthoclase (also plagioclase), biotite, and hornblende, with sometimes magnetite, apatite, epidote and zircon. Dr HATCH informs me that he finds that in some instances (Beinn-an-Dubhaich) the quartz contains minute inclusions (glass?), bearing immovable bubbles with strongly marked contours; while in others (Beinn-na-Chro, Skye), this mineral is full of liquid inclusions with bubbles, sometimes vibratile, sometimes fixed. He remarks that the quartz and felspar have consolidated almost simultaneously, but that in some instances

* Karsten's *Archiv*, i. p. 89.

(Marsco, Glen Sligachan) there are isolated roughly idiomorphic crystals, of a white, less turbid orthoclase, which belong to a slightly earlier consolidation than that of the more kaolinised felspar of the rest of the rock.

With the Tertiary volcanic series of the West Highlands, I have little doubt that the granite of the island of Arran should be classed. In 1873 I gave my reasons for believing this rock to be of so recent date,* and subsequent microscopic examination has tended to confirm this inference by showing the occasional presence in the Arran granite of the same granophyric structure so characteristic of the acid rocks of Skye and Mull.† The granite of the Mourne Mountains has been shown by the Irish Geological Survey to be younger than some of the basic dykes of the south-east of Ireland, and older than others.‡ And microscopic evidence in this case also links that rock with the granophyres of the west of Scotland.

§ 2. Types of Structure.

In the history of opinion regarding the relative position of the Tertiary eruptive rocks, no point has struck me more than the universal acceptance of what I must now term the misconception regarding the place of the acid protrusions. In tracing this mistake to its source, we find that it probably arose from the fact that along their line of junction the granitoid masses generally underlie the basic. This order of superposition, which would usually suffice to fix the age of two groups of stratified rocks, is obviously not of itself enough to settle the relative epochs of two groups of intrusive rocks. Yet it has been assumed as adequate for this purpose, and hence what can be proved to be really the youngest has been placed as the oldest part of the Tertiary volcanic series.

MACCULLOCH, who showed that his "syenites" and "porphyries" had invaded the Secondary strata of the Inner Hebrides, and must therefore be of younger date than these, left their relations to the other igneous rocks of the region in a curiously indefinite position. He was disposed to regard them all as merely parts of one great series; and seems to have thought that they graduate into each other, and that any attempt to discriminate between them as to relative age is superfluous. Yet he evidently felt that the contrasts of topography which he described could hardly fail to raise the question of whether rocks so distinct in outward form did not differ also in relative antiquity. But he dismissed the question without answering it, remarking that if there is any difference of age between the two kinds of rock, "there appears no great prospect of discovering it."§ He records an instance of a vein of "syenite" traversing the "hypersthene rock" in the valley of Coruisk. "If this vein," he says, "could be traced to the mass of syenite, it might be held a sufficient ground of judgment, but under the present circumstances, it is incapable of affording any assistance in solving the difficulty."|| Instead,

* *Trans. Edin. Geol. Soc.*, vol. ii. part 3.

† See Mr TEALL's *British Petrography* (1888), p. 328.

‡ Explanation to Sheets 60, 61, and 71, *Geol. Survey, Ireland*, pp. 16, 30.

§ *Western Islands*, i. p. 368; see also pp. 488, 575, 578.

|| *Op. cit.*, p. 370.

however, of being a solitary instance, it is only one of hundreds of similar intrusions, which can be connected with the general body of granitoid and porphyritic rocks, and which put the relative ages of the two groups of rock beyond any further doubt.

BOUÉ, who knew the geology of some of the extinct volcanic regions of Europe, recognised the similarity of the Scottish masses to those of the Continent, and classed the acid rocks as "trachytes." He saw in each of the volcanic areas of the west of Scotland a trachytic centre, and supposed that the more granitoid parts might represent the centres in the European trachytic masses. He traced in imagination the flow of the lava-streams from these foci of volcanic activity, distinguishing them as products of different epochs of eruption, among the last of which he thought that the trachytic porphyries might have been discharged. He admitted, however, that his restoration could not be based on the few available data without recourse to theoretical notions drawn from the analogy of other regions.*

In the careful exploration of the central region of Skye made by VON OEYNHAUSEN and VON DECHEN, these able observers traced the boundary between the "syenite" and the "hypersthene rock"; and as they found the former lying underneath the latter, they seem naturally to have considered it to be the older protrusion of the two.† Principal FORBES came to a similar conclusion from the fact that he found the dark gabbro always overlying the light-coloured felspathic masses.‡ Professor ZIRKEL also observed the same relative position, and adopted the same inference as to the relative age of the rocks.§ Professor JUDD followed these writers in placing the acid rocks before the basic. He has supposed the granitoid masses to form the cores of volcanic piles probably of Eocene age, through and over which the extrusions of gabbro and the eruptions of the plateau-basalts took place.||

Among the protrusions of acid rocks in the Tertiary volcanic areas of Britain four distinct types of structure may be noted, viz. (1) bosses, (2) sills or intrusive sheets, (3) veins and dykes, and (4) superficial lava-streams. Of these the first three belong entirely to the underground operation of volcanism, the last is the only one which reveals the outflow of material at the surface.

1. *Bosses.*

These are irregular protrusions varying in size from knobs measuring only a few square yards up to huge masses many square miles in extent, and comprising groups of lofty hills. As a rule, their outlines are markedly irregular. Beneath the surface they plunge down almost vertically through the rocks which they traverse, but in not a few instances their boundaries are inclined to the horizon so that the contiguous rocks seem

* *Essai Géologique sur l'Écosse*, pp. 291, 322, 327.

† Karsten's *Archiv*, i. p. 82.

‡ *Edin. New Phil. Jour.*, xl. (1846) p. 84.

§ *Zeitsch. Deutsch. Geol. Gesellsch.*, xxiii. (1871) pp. 90, 95. He says that the gabbro seems to be the younger rock, so far as their relations to each other can be seen.

|| *Quart. Jour. Geol. Soc.*, xxx. p. 255.

to rest against them, and sometimes lie in outliers on their sides and summits. From the margins of these bosses veins are given off into the surrounding rocks, sometimes only rarely and at wide intervals, in other places in prodigious numbers.

The rock of which the bosses consist is generally granitoid in texture, passing on the one hand, particularly in the central parts, into a truly granitic character, and on the other, and especially towards the margin, into granophyre, quartz-porphyry, and various compact felsitic varieties, and sometimes exhibiting along the outer edge a more or less developed flow-structure.

Decided contact metamorphism is traceable round the bosses, but is by no means uniform even in the same rock, some parts being highly altered, while others, exposed apparently to the same influences, have undergone little change. The most marked examples of this metamorphism are those in which the Lower Silurian limestone of Skye has been converted into a pure white saccaroid marble.* But the most interesting to the student of volcanic action are those where the altered rocks are older parts of the volcanic series. As the bosses of each volcanic area offer distinctive peculiarities they will here be described geographically.

a. MULL.—Though of comparatively small extent the bosses of the island of Mull probably afford to the geologist a larger amount of instruction than those of any other district. Especially important is the evidence which they contain of the true relations of the acid and basic groups of rocks. They have been laid bare in many natural sections, some of which, forming entire hill sides, are among the most astonishing in the whole wonderful series which, laid open by denudation, reveal to us the structure of these volcanic regions. They lie in two chief areas. One of these extends along the northern flanks of the mountainous tract from the western side of Beinn Fhada across Loch Ba' to the west side of Glen Forsa. The other occupies for over three miles the bottom of Glen More, the deep valley which, skirting the southern side of the chief group of hills, connects the east side of the island by road with the head of the great western inlet of Loch Scridain. There are other minor areas. One of these extends for about a mile along the declivities to the south of Salen, across the valley of the Allt na Searmoin; another occurs at Salen, a third runs along the shore at Craignure. In the interior also, many isolated areas of similar rocks, besides thousands of veins, occur in the central group of hills and valleys which form the basins of the Glencannel and Forsa rivers.

The chief northern boss, which for the sake of convenience of reference may be called that of Loch Ba', has a length of nearly six miles, with a breadth varying from a quarter of a mile to about a mile and a quarter. It descends to within fifty feet of the sea-level, and is exposed along the crest of Beinn Fhada at a height of more than 1800 feet. It chiefly consists of a grey crystalline rock which might readily be identified as a granite, but which when examined microscopically is found to possess the granophyric structure. But with this distinctly granular-crystalline rock are associated various

* This marble was believed to be altered Lias; but I have proved it by lithological, stratigraphical, and palæontological evidence to be Lower Silurian (*Quart. Jour. Geol. Soc.*, xliv. (1888) p. 62).

porphyritic and felsitic masses, which pass into it, and are more specially observable along its border. An exceedingly compact black quartz-felsite forms its southern boundary, runs as a broad dyke-like ridge from the head of the Scarrisdale Water, north-eastward across Loch Ba' (fig. 43), and spreads out eastward into a mass more than a mile broad on the heights above Kilbeg in Glen Forsa. The sharp line of demarcation of this felsite, and its mass and extent, point to different periods of extravasation in the Loch Ba' boss.

The geologist, who approaches this district from the north-east, has his attention arrested, even at a distance of several miles, by the contrast between the outer and inner parts of the hills that lie to the south-west of Loch Ba'. He can readily trace from afar the dark bedded basic rocks rising terrace above terrace from the shores of Loch na Keal to form the sea-ward faces of the hills along the southern side of that fjord. But he observes that immediately behind these terraces the mass of the rising ground

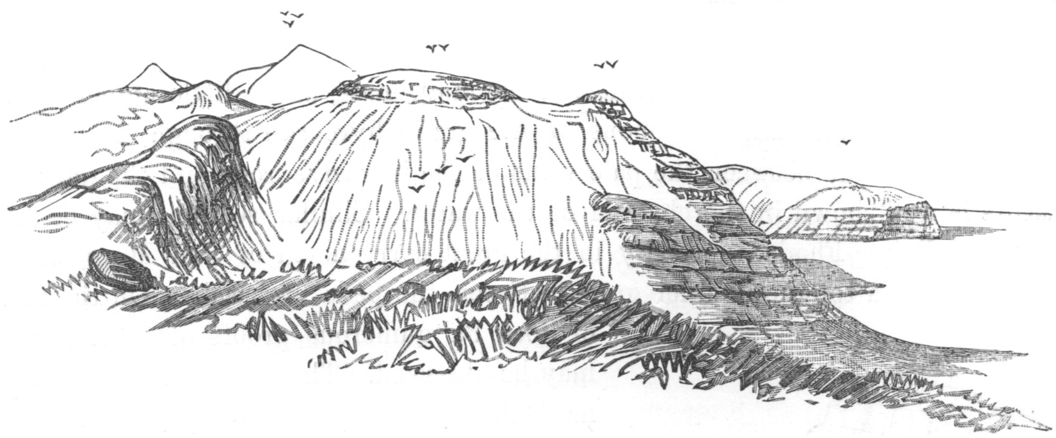


Fig. 43.—View of the hills on the south side of the head of Loch na Keal, showing the junction of the Granophyre and the Bedded Basalts. One bird, the bedded basalts of the Gribon plateau; two birds, the bedded dolerites and basalts of Beinn a' Chraig adhering to the northern slope and capping the hill; three birds, summit of Ben More, with A'Chioch to the left and the top of Beinn Fhada appearing in the middle distance between them; four birds, the granophyre slopes of Beinn a' Chraig with the great dyke-like mass of felsite on the left.

obviously consists of some amorphous rock which weathers into white débris. Nothing can be sharper than the contrast of colour and form between the two parts of the hills. The bedded plateau-rocks lie as a kind of wall or veneer against a steep face of the structureless interior (fig. 43). Seen from the other or hilly side, the contrast is perhaps even more striking. But the astonishment with which it is beheld at a distance becomes intensified when one climbs the slopes, and finds that the sheets of dolerite and basalt (which from some points of view look quite level, yet dip towards the north-east at a gentle angle), are immediately behind the declivity abruptly truncated by a mass of granophyre. So little disturbed are they, that one's first impulse is to search for pebbles of the granophyre between the basalts, for it seems incredible that the inner rock should be anything but a central core of older eruptive material, against and round which the younger basic rocks have flowed. But, though the granophyre is so decomposing and covers its slopes with such "screes" of débris, that had the basalts been poured round it, they must infallibly have had some of its fragments washed down between their successive flows, not a single pebble of it is there to be found. This might not be considered decisive evidence, but it is extended and confirmed by the fact that the acid rock gives off veins which ramify through the basalts.

In the bed of the south fork of the Scarrisdale stream, a separate boss of granophyre (which under the microscope exhibits in perfection the characteristic structure of this rock),

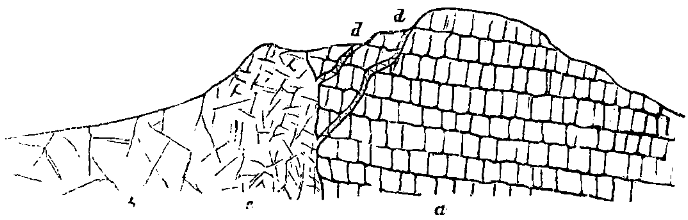


FIG. 44.—Section on south side of Cruach Tòrr an Lochain, Mull. *a*, bedded basalts and dolerites; *b*, granophyre; *c*, felsitic band; *dd*, veins of felsite traversing the basic rocks.

protrudes through the basalts in advance of the main mass, and a little higher up on the outskirts of that mass narrow ribbons of the granophyre run through the basic rocks. The contrast of colour between the pale veins of the intrusive rock and the dark tint of the basalts is well shown in the channel of the water. Similar sections may be seen on the flanks of Beinn Fhada, especially in the great corry north of Ben More, where the granophyre sends a tongue of finer grain between the beds of basalt. On the east side of Loch Ba' numerous proofs of similar intrusion may be observed. Thus at the east end of Loch na Dàiridh, where the granophyre has been intruded into the basalts, hand-specimens may be obtained showing the two rocks welded together. On the slopes of Cruach Tòrr an Lochain, where the granophyre has a felsitic selvage, the bedded basalts are traversed by veins of the latter material (fig. 44). A little further east, at the head of the Allt na Searmoin, the bedded basalts, some of which are separated by slaggy scoriaceous surfaces, are intersected by another protrusion from the compact felsitic porphyry (fig. 45).* A mile lower down the same valley a separate mass of granophyre sends out veins into the basalts.

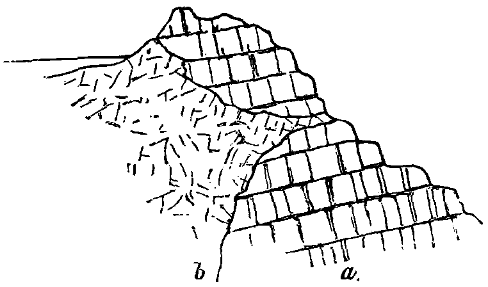


FIG. 45.—Section at head of Allt na Searmoin, Mull. *a*, basalts and dolerites, with slaggy upper surfaces; *b*, felsite.

As the posteriority of the granophyre and felsites to the basalts is thus proved, the further question remains as to their mode of intrusion. Here and there, especially on

* This rock appears to the eye as a black finely crystalline-granular felsite. Under the microscope "it presents a markedly granulitic structure, consisting mainly of small rounded grains of dirty brown turbid felspar, with isolated granules of colourless quartz. Scattered through the rock, or accumulated in patches, are small spherical or drop-like granules of a bright green augite (coccolite)."—Dr HATCH.

the south-eastern side, between the head of the Scarrisdale river and Loch Ba', the line of junction between the two rocks is nearly vertical, but a body of black felsite intervenes as a huge wall between the ordinary granophyre and the basalt. On Beinn Fhada and Beinn a' Chraig the line of separation, as I have above remarked, is inclined outwards, and plunges under the basalts at an angle of 30° to 40°. The terraced basalts and dolerites are not sensibly disturbed, but end off abruptly against the steep face of intrusive rock. We might suppose that in this case the younger rock had merely carried upward the continuation of the beds that are truncated by it. But on the top of the ridge of Beinn a' Chraig we find that the outliers which there remain are not portions of the lower basalts, but of the upper pale group of Ben More. The same rocks are prolonged on the other side of the Scarrisdale Glen, sweep over the summit of Beinn Fhada, and run on continuously into the crest of A'Chioch and the upper part of Ben More. The granophyre has usurped the place of the lower dolerites and basalts, but has left the felspathic lavas of the "pale group" in their proper position. And to make this remarkable structure still more clear, sections may be seen on the southern flanks of Beinn Fhada, where the upper surface of the granophyre comes down obliquely across

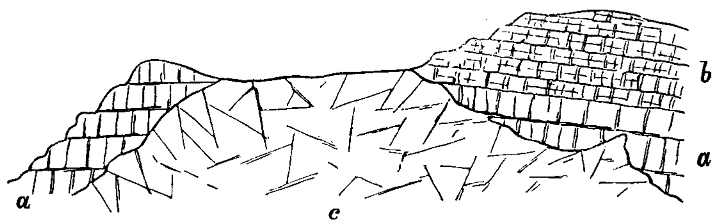


FIG. 46.—Section on south side of Beinn Fhada, Mull. *aa*, bedded basalts and dolerites; *b*, "pale group" of Ben More; *c*, granophyre.

the edges of the lavas, and allows the junction of the basalts and the "pale group" to be seen above it (fig. 46).

Contact metamorphism has been produced around this intrusive boss. It is most marked in the outliers that cap Beinn a' Chraig and on the two ridges to the south-west. In the field, it is seen to consist in a high degree of induration, the production of a shattery irregularly jointed structure, and the effacement of the obvious bedding which characterises the unaltered rocks. The microscopic changes will be described on a later page, together with those of other districts.

The position of this eruptive mass, quite a mile broad, breaking through, without violently tilting them, more than 1800 feet of the bedded basalts, and then stopping short about the base of the "pale group," presents a curious problem to the student of geological physics. It at once reminds him of many sections among Palæozoic granites where an eruptive boss has ascended and taken the place of an equivalent volume of the surrounding rocks, which, though more or less metamorphosed, are not made to dip away from it as from a solid wedge driven upwards through them. In this Mull case, however, there are some peculiar features that deserve consideration, for they seem to show that here as elsewhere passages for the uprise of the intrusive rock were already provided by the presence of volcanic pipes, which, even if filled up with fragmentary materials, would no doubt continue to be points of weakness. Round the flanks of the Loch Ba' boss, and here and there on its surface, patches of intensely indurated volcanic agglomerate may be detected. A little to the south of the tarn called Loch na Dàiridh, the granophyre is succeeded by the black flinty felsite already referred to. This rock in some places exhibits a beautiful flow-structure, with large porphyritic felspars, and incloses a great many fragments of dolerite and gabbro, varying from the size of a pea up to blocks several inches in diameter. Lying on its surface are detached knolls of much altered dolerite, basalt, and coarse breccia or agglomerate. On its southern margin one of these patches of agglomerate contains abundant fragments of various felsitic rocks, among which are pieces of a compact rock with flow-structure like that found in place immediately to the north; also rounded pieces of quartzite, and of compact and amygdaloidal basalt wrapped up in a very hard matrix which seems to consist largely of basalt-dust. No bedding can be made out in this rock, and the mass looks like part of a true neck. Further down the slope the bedded basalts appear. The actual junctions of the different

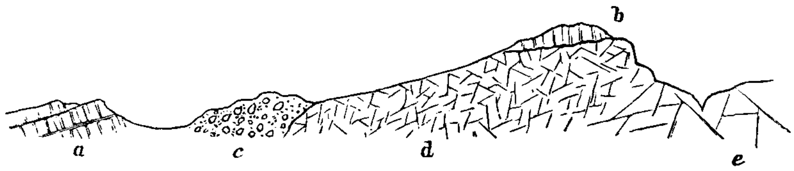


FIG. 47.—Section to south of Loch na Dàiridh, Mull. *a*, basalts; *b*, dolerites; *c*, volcanic agglomerate; *d*, black felsite; *e*, granophyre.

rocks cannot be satisfactorily traced, but the structure of the ground appears to me to be as shown in fig. 47. A patch of similar agglomerate appears a little to the south-west of the last section in front of a cliff of the felsite, and seems to be enclosed in the latter rock, and other exposures of agglomerate, underlain and intensely indurated by the felsite, may be noticed on the ground that slopes towards Loch Ba'.

That these agglomerates do not belong to the period of the eruption of the granophyre and felsite, but to that of the bedded basalts, may be inferred from their intense induration next the acid rocks, and also from the fact that similar breccias are actually found here interposed between the bedded basalts. This is well shown on the hill above the Coille na Sròine, where the accompanying section can be seen (fig. 48). The broad dyke-like mass of black flinty felsite already referred to runs as a prominent rib over the southern end of Beinn a' Chraig into the head of the Scarrisdale glen (see fig. 43). It cuts across the bedded basalts, and immediately to the south of where these appear, a thin intercalated bed of breccia crops out, of the usual dull-green colour, with abundant fragments of basalt and many of yellow and grey felsite.

From these various facts we may, I think, conclude that along the strip of ground now occupied by the Loch Ba' boss of granophyre and felsite, there once stood a line or group of small vents, from which, besides the usual basalt-débris, there were ejected many pieces of different felsitic (or rhyolitic) rocks, and that these eruptions of fragmentary material took place during the accumulation of the plateau-basalts. The existence of these volcanic funnels occasioned a line of weakness of which, in a long subsequent episode of the protracted volcanic period, the acid rocks took advantage, forcing themselves upwards therein, and leaving only slight traces of the vents which assisted their ascent.

The second or Glen More boss, instead of rising into hilly ground, is confined to the bottom of the main and tributary valleys, and has only been revealed by the extensive denudation to which these hollows owe their origin. It begins nearly a mile below Torness and extends up to Loch Airdeglais—a distance of almost four miles. Though singularly devoid of topographical feature, it exhibits with admirable clearness the relation of the granophyres to the gabbros, and thus deserves an important place among the tracts of acid rocks in the Western Islands. Its petrographical characters change

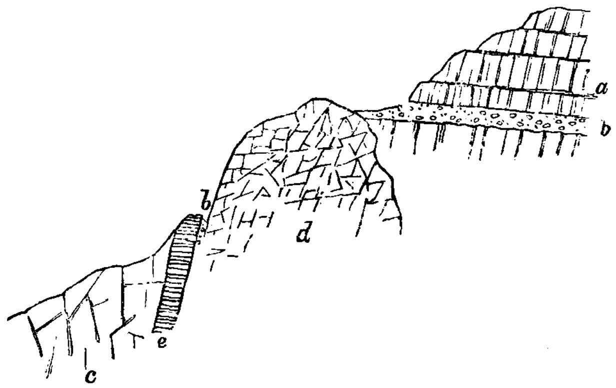


FIG. 48.—Section of junction of south side of Loch Ba' Granophyre boss, with the Bedded Basalts, Mull. *a*, bedded basalts; *bb*, basalt-tuff and breccia; *c*, granophyre; *d*, black felsite; *e*, coarse dolerite dyke, 30 or 40 feet wide.

considerably from one part of its body to another. For the most part, it is a true granophyre, sometimes with orthoclase, sometimes with plagioclase as its predominant felspar. At Ishriff, as already stated, it is sprinkled with long acicular decayed crystals of hornblende; but at the watershed the ferro-magnesian mineral is augite. The surrounding rocks are mainly the plateau-basalts, with their intruded sheets of dolerite and gabbro.

This strip of granophyre sends abundant apophyses from its mass into the dark basic rocks around it. Some of the best sections to show the nature of these offshoots are to be found on the steep hill-slope which mounts from the watershed in Glen More southward into the Creag na h-Iolaire (Eagle's Crag), and thence up into the great gabbro ridge of Ben Buy. From the main body of granophyre a multitude of veins ascends through the basalts and gabbros from 2 feet or more in breadth down to mere filaments. Even at a height of 300 feet up the hill some of these veins are still 3 inches broad, and present the usual granophyric structure, though rather finer in grain than the general mass of the boss, and sometimes assuming a compact felsitic or spherulitic texture at the immediate contact with the surrounding rock. One of the most striking proofs of the posteriority of these veins is furnished by the perfect flow-structure they not infrequently exhibit along their margins, their long felspar crystals being arranged parallel to the walls in lines that follow the sinuosities of the boundary between the two rocks (fig. 49). Patches of gabbro and of the indurated basalts may be seen lying on

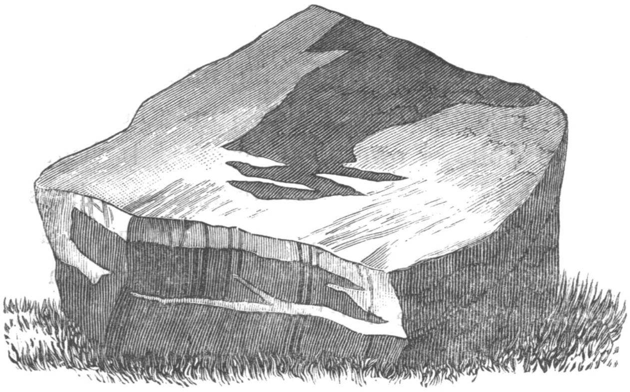


FIG. 49.—Mass of dark Gabbro about two feet in diameter traversed by pale veins of Granophyre, lying on north slope of Creag na h-Iolaire, Mull.

the granophyre, from which veins and strings ramify through them (fig. 50). Similar veins can be traced upward into the main body of coarse gabbro, forming the ridge of Ben Buy. Some of them are of the usual granular granophyric texture, others are dull fine-grained porphyries (claystones of the older authors).

Hence it is evident that the granophyres in Mull have been protruded not only after

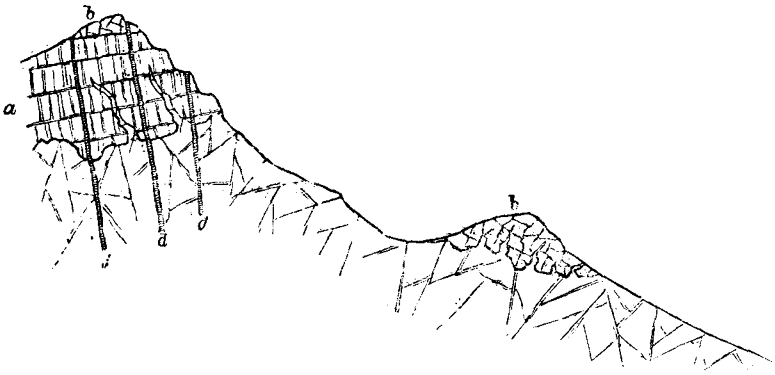


FIG. 50.—Section at Creag na h-Iolaire, Glen More, Mull, showing Basalts and Gabbros resting on and pierced by Granophyre. *a*, much indurated and altered basalts and dolerites; *bb*, gabbro; *c*, granophyre; *dd*, basalt dykes.

the accumulation of the plateau-basalts, but after these were traversed by the sheets and veins of gabbro. The amount of acid rock injected into these older rocks over the mountainous part of the island is enormous; but I reserve further reference to it for the section on dykes and veins, for these are the forms in which it chiefly occurs. It should be added, that in the localities here referred to basalt-veins and dykes are generally abundant, cutting through all the other rocks (fig. 50). So numerous are they that the geologist ceases to take note of them when his thoughts are engaged upon the problems presented by the masses through which they rise.

b. SMALL ISLES.—In the island of Eigg three small bosses or sheets occur. That at the northern end rises through the Jurassic sedimentary rocks, and forms a bold cliff from 150 to 200 feet high. It is a light grey granophyric porphyry, with rounded blebs of quartz in a micropegmatic base of quartz and felspar. The other two masses, of smaller size, cut through the bedded basalts.*

In the opposite island of Rum, the acid protrusions play a much more important part. On the east side of the hills, they occur in sheets at the base of the gabbros; on the west side, they form a large tract of hilly ground, which, stretching along the coast line for about three and a half miles from the headland of A' Bhrideanach to Harris, forms there a range of shattered sea-cliffs, parts of which tower for 1000 feet above the Atlantic breakers that beat about their base. The area extends inland to the slopes on the west side of Loch Sgathaig, a distance of about three and a half miles, descending in a range of precipices along its northern front, and reaching in its culminating summit, Orval, a

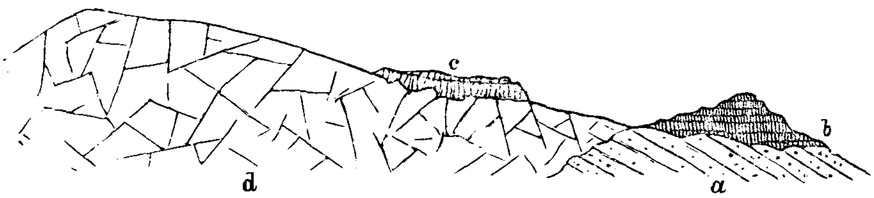


FIG. 51.—Section on north side of Orval, Rum. *a*, Cambrian sandstones; *b*, bedded basalts of Fionn Chro; *c*, dolerite; *d*, quartz-porphyry.

height of 1868 feet above the sea. The rocks of which this triangular area consists resemble those of the Mull bosses. They are chiefly quartz-porphyries, becoming felsitic in texture towards their contact with adjacent rocks. In some places, as was noticed by MACCULLOCH on the sea-cliffs,† they have a rudely bedded structure. Thus on the north-west front of Orval, this structure is shown by parallel planes that dip outwards or NW. at 30° to 40°, and which are made still more distinct by an occasional intrusive dyke or sheet of basalt between their surfaces. I shall again have occasion to refer to the internal arrangement of the granitoid bosses, in the account of those of Skye.

Like the gabbros already noticed, the granophyres, porphyries, and felsites of Rum have been intruded at the base of the volcanic series, and over much, if not all, of their area lie directly on the red Cambrian (Torridon) sandstone. That the bedded basalts once covered them is shown by the position of the three outliers of the basalt-plateau already noticed. But a fourth outlier still lies upon the porphyry of Orval as a cake that dips gently northward. It consists of a bedded, dark, finely crystalline, ophitic dolerite, porphyritic in places, with a rudely prismatic or columnar structure (fig. 51). It has undergone contact metamorphism, and tongues from the underlying rock project up

* *Quart. Jour. Geol. Soc.*, xxvii. (1871) p. 294.

† *Western Islands*, vol. i. p. 487.

into it. On the south-eastern side of the same hill, still more striking evidence is presented of the posteriority of the acid to the basic rocks. The porphyry shows here the same tendency to assume a bedded structure, the parallel "beds" again dipping outward or SE. at 40°. They plunge under the body of gabbro, dolerite, and other intrusive masses which from this point stretch eastward into the great cones of Allival and its neighbours. The rock at the junction is a fine microgranite with traces of micropegmatite. It is composed of a holocrystalline base of quartz and orthoclase, with porphyritic crystals of microcline, blebs of quartz and scattered granules of augite. The rocks that rest immediately next it are basalt and dolerite, into which it has sent an intricate network of veins (fig. 52).* It sends also long tongues down the slope into these rocks, some of which may be seen traversing the dolerite and gabbro veins that cut the basalts. The basic rocks next the porphyry have been intensely altered. They seem in places as if they have been shattered by some explosive force, and had then been invaded by the mass that rushed into all the rents thus caused. The nature of the contact metamorphism produced by the acid protrusions is described at p. 167.

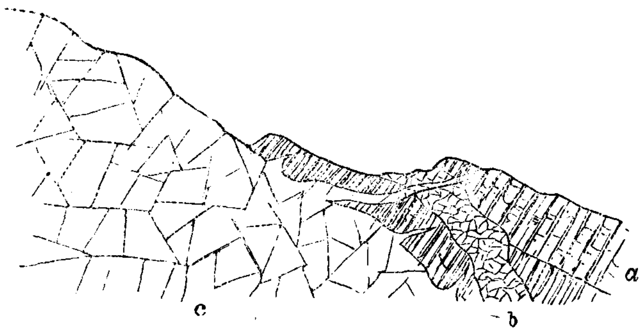


FIG. 52.—Junction of Quartz-Porphyry (Microgranite) and Basic Rocks, south-east side of Orval, Rum. *a*, basalts and dolerites; *b*, dolerite and gabbro veins; *c*, quartz-porphyry cutting *a* and *b*.

c. SKYE.—It is in the island of Skye that the granitoid bosses attain their largest dimensions. They cover there a total area of about 25 square miles, and form characteristic groups of hills from 2000 to 2500 feet in height. On the south-east side, a group of three conspicuous cones rises from the valley of Strath (Beinn Dearg Mhor Beinn Dearg Bheag, and Beinn na Caillich). A solitary graceful pointed cone (Beinn na Cro) stands between Strathmore and Strathbeg, while to the north-west a continuous chain of connected cones runs from Loch Sligachan up into the heart of the Cuillin Hills. Their conical outline, their smooth declivities, marked with long diverging lines of screes, and their pale reddish or reddish-yellow hue, that deepens after a shower into glowing orange, mark off these hills from all the surrounding eminences, and form in especial a singular contrast to the black, spiry, and rugged contours of the gabbro heights to the west of them.

Besides this large continuous mass, a number of minor bosses are scattered over the district. Of these the largest forms the ridge of Beinn an Dubhaich, south of Loch

* In a thin slice cut from a specimen showing the junction, there is a minute vein of the porphyry penetrating the basalt which is much altered, while the porphyry becomes much finer in grain than at a distance from the contact.

Kilchrist. Several minor protrusions lie between that ridge and the flank of Beinn Dearg. Another forms the moory ground above Corry; several occur on the side of the Sound of Scalpa, about Strollamus; and one, already referred to, lies at the eastern base of Blath Bheinn.

In so extensive a tract, there is room for considerable diversity of composition and texture among the rocks of which it consists. I have already stated that in some places, more particularly in the central parts of the hills, the rock assumes the character of a granite, being made up of a holocrystalline aggregate of quartz, orthoclase, plagioclase, hornblende, and biotite, without granophyric structure. It is then a hornblende-biotite-granite (quartz-syenite, granite-syenite of ZIRKEL, or amphibole-granitite of ROSENBUSCH). By the development of the micropegmatitic structure and radiated spherical concretions, it passes into granophyre. By the appearance of a felsitic ground-mass, it shades off into different varieties of quartz-porphyry (rhyolite of some authors), sometimes with distinct bi-pyramidal crystals of quartz.* As it is convenient to adopt some general term to express the whole series of varieties in the Skye area, I shall use the word granophyre for this purpose.

That the large area of these rocks in Skye must have been the result of many separate protrusions from distinct centres of emission may be inferred, I think, not only from the varieties of petrographical character in the material, but also from the peculiar topography of the ground, and perhaps from the curious relation which seems, in some instances at least, to be traceable between the external features and apparent internal structure of the hills. It will seen from the map (Plate II.) that in the area lying to the east of Strath More, the granophyre is broken up into nearly detached portions by intervening patches of older rocks. There can be little doubt that the mass of Beinn na Caillich and the two Beinn Deargs is the product of a distinct orifice, if not of more than one. Beinn na Cro, lying between its two deep bounding glens, is another protrusion. The western cones stand so closely together that their screes meet at the bottoms of the intervening valleys. Yet each group is not improbably the result of emission from an independent funnel.

But, though I believe this large area of granitoid rock to have proceeded not from one but from many orifices, I have only here and there obtained, from the individual hills themselves, indications of an internal structure suggestive of distinct and successive protrusions of material from the same vent of discharge. On the outer declivities of some of the cones, we may detect a repetition of that rudely bedded structure to which reference has been made as occurring in Rum. This structure is specially observable along the east side of Glen Sligachan. Down the northern slopes of Marsco the granophyre (here in part a hornblende-biotite-granite) is disposed in massive sheets or beds that plunge outwards from the centre of the hill at angles of 30° to 40°. On the southern front of the same graceful cone, as well as on the flanks of its neighbour, Ruadh

* The best account yet published of these varieties in Skye is that by Prof. ZIRKEL, *Zeitsch. Deutsch. Geol. Gesellsch.*, xxiii. (1871) p. 88.

Stac, still plainer indications of a definite arrangement of the mass of the rock in irregular lenticular beds may be noticed. These beds, folding over the axis of the hill, dip steeply down as concentric coats of rock. The external resemblance of the red conical mountains of Skye to the trachyte *puys* of Auvergne was long ago remarked by J. D. FORBES,* and in this internal arrangement of their materials, indefinite though it may be, there is a further resemblance to the onion-like coatings which SCROPE thought he could detect in the interior of the Grand Sarcoui.†

Where the contour of the cones is regular, and the declivities are not marked by prominent scars and ribs of rock, this monotony of feature betokens a corresponding uniformity of petrographical character. But where, on the other hand, the slopes are diversified by projecting crags and other varieties of outline, a greater range of texture and composition in the material of the hills is indicated. This relation is well brought out on the western front of Marsco, where numerous alternations of granitoid and felsitic textures occur. On many declivities also, which at a distance look quite smooth, but which are really rough with angular blocks detached from the parent mass underneath, an occasional basalt-dyke will be observed to rise as a prominent dark rib. A good example of this structure is to be seen on the south front of Beinn na Caillich. Where a group of dark parallel dykes runs along the sides of one of these pale cones it sometimes produces a curiously deceptive appearance of bedding. A good illustration may be noticed on the southern front of Beinn Dearg Meadhonach, north from Marsco. When I first saw that hillside I could not realise that the parallel bars were actually dykes until I had crossed the valley and climbed the slopes of the hill.‡

Occasionally round the margin of the granophyre a singular brecciated structure is to be seen. It is most marked on weathered faces, and may be observed on the flanks of Glamaig and of Marsco. But when the rock is broken open, it is less easy to detect the angular and subangular fragments from the surrounding matrix, which is finely crystalline or felsitic.

The actual junction of the eruptive mass with the surrounding rocks through which it has ascended is generally a nearly vertical boundary, or the granophyre plunges at a steep angle under the rocks that lie against or upon it. On the north of Glamaig, for instance, the porphyritic and felsitic margin of the great body of eruptive rock descends as a steeply inclined wall, against which the red sandstones and marls at the base of the Secondary formations are sharply tilted. On the south side of the area, a similar steep face of fine-grained rock forms the edge of the granophyre of the great southern cones, and plunges down behind Lias limestone and shale, Lower Silurian limestone and quartzite, or portions of the Tertiary volcanic series. Yet there can be no doubt that, along many parts of the boundary-line, the eruptive mass extends underneath the surface

* *Edin. New Phil. Jour.*, xl. p. 78.

† *Geology and Extinct Volcanoes of Central France*, 2d edit., p. 68.

‡ The difference of contour and colour between the ordinary reddish smooth-sloped "syenite" and the black craggy "hypersthene rock" and "greenstone" at the Glamaig group of hills caught the eyes of VON OYENHAUSEN and VON DECHEN (Karsten's *Archiv*, i. p. 83).

far beyond the actual base of the cones, for projecting knobs as well as veins and dykes of it rise up among the surrounding rocks. This may be well seen along the northern foot of Beinn na Caillich. But of all the Skye bosses none exhibits its line of junction with the surrounding rocks so well and continuously as Beinn an Dubhaich. This isolated tract of eruptive material lies entirely within the area of the Lower Silurian limestone, and its actual contact with that rock, and with the basalt-dykes that traverse it, can be examined almost everywhere. The junction is usually vertical or nearly so, sometimes inclining outwards, sometimes inwards. It is notched and wavy, the granophyre sending out projecting spurs or veins, and retiring into little bays which are occupied by the limestone. The rock of the boss is massive and jointed, splitting up into great quadrangular blocks like a granite, and weathering into rounded boulders. It is in some parts a hornblende-biotite-granite, its granitic composition and texture being best seen where the mass is broadest, south of Kilbride. Towards its margin, on the shore of Camas Malag, the granophyric structure appears especially in narrow ribbons or veins that run through the more granitic parts of the rock.

Immediately to the south of this bay, the junction with the limestone is well displayed, and the eruptive rock, which is there granitic in character, sends out into the limestone a vein or dyke about two feet broad, of closer grain than the main body of the boss, but showing a distinctly granitic structure. The junction on the north side is equally well seen below the crofts of Torran. Here the rock of the boss, for a few yards from its margin, assumes a fine-grained felsitic aspect, and under the microscope presents a curious brecciated appearance, suggestive of its having broken up at the margin before final consolidation. Portions of the already crystallised granite seem to be involved in a micrograniti base. The rock has here truncated a number of basalt-dykes which intersect the Silurian limestone.

On the surface of the mass of Beinn an Dubhaich, a few little patches of limestone occur to the south of Kilchrist Loch. Considering the nearly vertical wall which the granophyre presents to the adjacent rock all round its margin, we may perhaps reasonably infer that these outliers of limestone are remnants of a once continuous limestone sheet that overlay the eruptive rock, and hence that, with due allowance for considerable denudation, the present surface of the boss represents approximately the upper limit to which the granophyre ascended through the limestone. The actual facts are shown in fig. 53.

All round the margin of this boss, the limestone has been converted for a variable distance of a few feet or many yards into a granular crystalline marble. The lighter portions of the limestone have become snowy white; but some of the darker Carbonaceous beds retain their dark tint. The nodules of chert, abundant in many of the limestones, project from the weathered faces of the marble. The dolomitic portions of the series have likewise undergone alteration into a thoroughly crystalline-granular or saccaroid rock. The most thorough metamorphism is exhibited by portions of the limestone which are completely surrounded by and rest upon the granophyre. The largest of these overlying patches was many years ago quarried for white marble above the old Manse of Kilchrist. I have recently shown that this limestone, instead of belonging to the Lias, forms a part of the Lower Silurian series, being a continuation of the fossiliferous limestone of western Sutherland and Ross-shire.*

The generally vertical line of separation between the rock of Beinn an Dubhaich and the contiguous limestone has been taken advantage of for the segregation of mineral veins. On the southern boundary at Camas Malag, a greenish flinty layer, from less than an inch to two or three inches in width, consisting of a finely granular aggregate of some nearly colourless mineral, which polarises brilliantly, coats the wall of the granophyre, and also both sides of the vein which proceeds from that rock into the limestone. But the most abundant and interesting deposits are metalliferous. Fragments of a kind of "gossan" may be noticed all along the boundary-line of the boss, and among these are pieces of magnetic iron-ore and sulphides of iron and copper. The magnetite may be seen in place immediately to the south of Kilbride. A mass of this ore several feet in diameter sends strings and disseminated particles through the

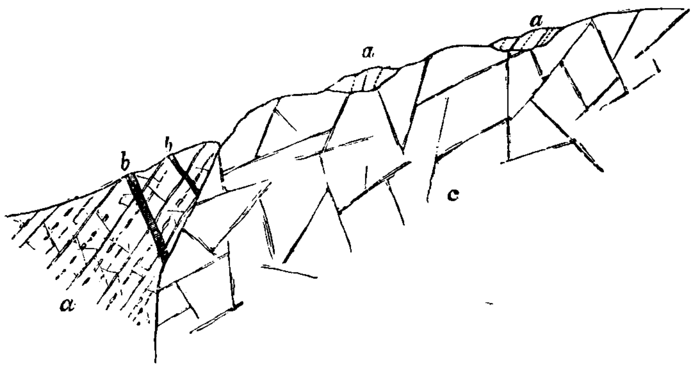


FIG. 53.—Section across the north slope of Beinn an Dubhaich. *aa*, Lower Silurian limestone; *bb*, basalt dykes; *c*, granophyre.

surrounding granophyre, and is partially coated along its joints with green carbonate of copper.

Relations of the Granophyre to other Members of the Volcanic Series.—It is the connection of the eruptive bosses of acid rocks with the other members of the volcanic series that is chiefly of interest for the purpose of the present memoir. From the Skye area, important evidence is obtainable in regard to the relation of these bosses to (1) earlier eruptive vents filled with agglomerate; (2) the bedded basalts of the plateaux; (3) the sheets and bosses of gabbro and dolerite; and (4) the great system of basic dykes.

(1) *Relation to older Eruptive Vents.*—The granophyre of Beinn na Caillich and the two Beinn Deargs has invaded on its north-eastern side the Lower Silurian limestone and quartzite, and has truncated the sheets of intrusive dolerite and gabbro that have there been injected into them. But to the south-west it rises through the great mass of agglomerate already described, and continues in that rock round to the entrance into

* *Quart. Jour. Geol. Soc.*, vol. xliv. (1888) p. 62.

Strath Beg. Judging from the respective areas of the granophyre and agglomerate, we may infer that the former has not risen here exactly in the centre of the old funnel, but rather to the north of it. It is no doubt this fortunate divergence that has spared a segment of the vent from obliteration. It is interesting to observe, however, that the granophyre has likewise risen along the outer or southern margin of the agglomerate, generally between that rock and the limestone, but sometimes entirely within the agglomerate. The distance between the nearest part of this ring of eruptive rock and the edge of the boss of Beinn an Dubhaich is under 400 yards, the intervening space being occupied by limestone (or marble), much traversed by N.W. basalt-dykes. These dykes do not enter the rocks of the vent, and are abruptly truncated by the mass of Beinn an Dubhaich. The structure of this locality in shown in fig. 54. Further westward, the group of vents, which as we have seen probably rose out of the plateau basalts, first served for the rise of the masses of gabbro, and the subsequent protrusion of the granophyres has destroyed or concealed any relics of it that might have survived.

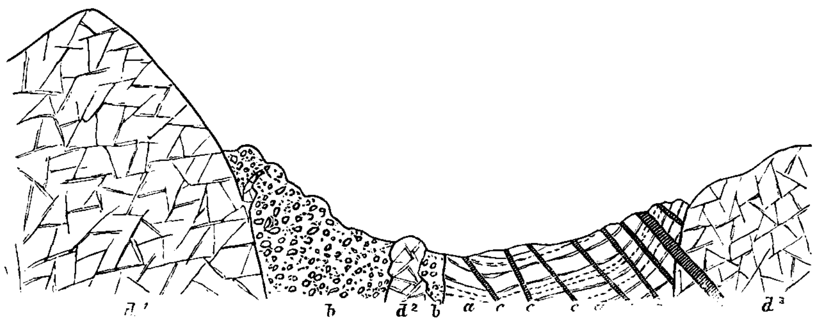


FIG. 54.—Section from Beinn Dearg to Beinn an Dubhaich, Skye. *aa*, Lower Silurian limestone; *bb*, volcanic agglomerate; *ccc*, basalt-dykes older than granophyre; d^1, granophyre of Beinn Dearg; d^2, granophyre in the agglomerate neck; d^3, granophyre of Beinn an Dubhaich; *e*, basalt-dyke younger than granophyre.

(2) *Relation to the Bedded Basalts of the Plateaux.*—On the north-west side, the granophyre of Glamaig and Glen Sligachan mounts directly out of the bedded basalts. These latter rocks, which rise into characteristic terraced slopes on the north side of Loch Sligachan, appear on the south side immediately to the west of Sconser, and stretch westwards round the roots of Glamaig into the Coire na Sgairde. As they approach that hill they assume the usual dull, indurated, splintery, veined character, where they have undergone contact metamorphism, and weather with a light crust. Some of them are highly amygdaloidal, and between their successive beds thin bands of basalt-breccia, also much hardened, occasionally appear. Veins of granophyre become more numerous as we come nearer the main mass of that rock. The actual line of junction runs into the Coire na Sgairde and slants up the Druim na Ruaige, ascending to within a few feet of the top of that ridge. A dark basic rock lies on the granophyre, the latter being here finer grained and greenish in colour, and projecting up into the former. There is so much detritus along the sides and floor of Glen Sligachan that the relations of the

two groups of rock cannot be well examined there. But the basalts, which present their ordinary characters to the north of the Inn, are observed to become more and more indurated, close-grained, dull, and splintery as they draw nearer to the granophyre of Marsco. This part of the district furnishes the clearest evidence of the posteriority of the great cones of Glamaig and its neighbours to the plateau-basalts which come up to the very base of these hills.

Round the eastern group of cones some interesting fragments of the once continuous sheet of basic rocks remain, to show the same relation of the acid protrusions on that side. One of these lies on the granophyre of the flanks of Beinn na Caillich, a little to the west of the loch at the northern base of that hill. Another of larger size forms a prominent knob about three-quarters of a mile further west, and is prolonged into the huge dark excrescence of Creagan Dubha, which rises in such striking contrast to the smooth red declivities of the granophyre cones around it. This prominence at its eastern and northern parts consists of highly indurated splintery basalt in distinct beds, some of which are strongly amygdaloidal. The bedding is nearly vertical, but with an inclination inwards to the hill. Towards the south-west end a thin band of basalt-breccia makes its appearance between two beds of basalt. Its thickness rapidly increases southward until it is the only rock adhering to the granophyre. Beyond the foot of the hill, Lower Silurian limestone and quartzite occupy for some distance the bottom of Strath Beg, much invaded by masses of quartz-porphyry. At the summit of Creagan Dubha abundant veins run into the basic rocks from the granophyre, which, as usual, is finer grained towards the margin; and there are likewise veins of quartz-porphyry which, though their actual connection with the main mass of granophyre cannot be seen, are no doubt apophyses from it.

This outlier of altered basalt and breccia appears to me to be a fragment of the plateau-basalts which once overlay the Silurian rocks of Strath Beg, and were disrupted by the uprise of the granophyre. It continues to adhere to the wall of the eruptive mass that broke up and baked its rocks. Its breccia, passing southward into a coarse agglomerate, is doubtless a product of the same vent that discharged the great agglomerate mass above Kilbride and Kilchrist. I have already (p. 109) referred to what appears to be another outlier of the basalts on the south side of Beinn Dearg.

On the northern and southern flanks of Beinn na Cro, similar evidence may be observed of the posteriority of the granophyre to the basic rocks. Round the northern base of the hill a continuous tract of basalts, dolerites, and gabbros forms the ridge between Strathmore and Strathbeg. There is an admirable section of the relation of the two groups of rock on the eastern side of the western glen. Along the lower part of the declivity, coarsely-crystalline gabbros, like some of those in the Cuillin Hills, are succeeded by sheets of dolerite and basalt, the whole forming an ascending succession of beds to the summit of the ridge. The edges of these beds are obliquely truncated by the body of granophyre, which slants up the hill across them and sends veins into them. They are further traversed by basalt dykes, which here as almost everywhere abound (fig. 55).

On the south side of Beinn na Cro, highly indurated black and grey Lias shales and sandstones have been tilted up steeply and indurated by the eruptive rock of the hill; and at one place some 800 feet above the sea, a little patch of altered basalt, lying on the shale but close up against the steep declivity of granophyre, forms a conspicuous prominence on the otherwise featureless slope.

I have reserved for the present section of this memoir a fuller account of the metamorphism of the basalts, to which frequent allusion has been made as one of the evidences of the posteriority of the eruptive bosses of rock round which it occurs. The field-geologist observes that the basalts as they are traced towards these bosses lose their usual external character. They no longer weather into spheroidal blocks with a rich brown loam, but project in much jointed crags, and their hard rugged surface shows when broken a thin white crust, beneath which the rock appears black, dull, and splintery. They are generally veined with minute threads or strings of calcite, epidote, and quartz, which form a yellowish-brown network that projects above the rest of the weathered surface. Where they are amygdaloidal the kernels no longer decay away or drop out,

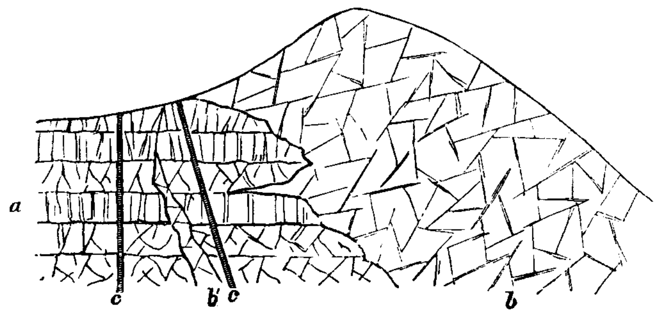


FIG. 55.—Section at north end of Beinn na Cro, Skye. *a*, basalt, dolerite, and gabbro; *b*, granophyre of Beinn na Cro; b^1, dyke of granophyre; *cc*, basalt dykes.

leaving the empty smooth-surfaced cells, but remain as if they graduated into the surrounding rock by an interlacing of their crystalline constituents. They then look at a distance more like spots of decoloration, and even when seen close at hand would hardly at first betray their real nature.

From the specimens collected by me in Skye, Mull, and Rum, I have selected two dozen which seemed to be fairly typical of these altered rocks, and have placed thin slices of them for microscopic examination in Dr HATCH's hands. His notes may be condensed into the following summary. One of the most frequent features in the slides is the tendency in the component minerals to assume granular forms. In one specimen from Loch Spelve, Mull, the rock, probably originally a dolerite, shows only a few isolated recognisable crystals of plagioclase and augite, the whole of the rest of the rock consisting of roundish granules embedded in a felspathic matrix. The felspar crystals are sometimes broken up into a mosaic, though retaining their external contours. Besides the granules, which are no doubt augite, a few grains of magnetite are scattered through the rock, aggregated here and there into little groups. In another specimen, taken from the junction with the granophyre in Glenmore in the same island, parts of the augite crystals are converted into granular aggregates associated with large grains and patches of magnetite. The latter mineral also assumes in some of the rocks granular and even globular shapes suggestive of fusion.

The felspars, which in most of the basic rocks are usually remarkably clear and fresh, show marked kaolinisation in these altered masses. Minute dusky scales of kaolin are developed in them, sometimes also with the separation of minute grains of quartz. The augite shows frequent alteration to hornblende, proceeding as usual from the exterior inward. In some cases only an envelope of uralite appears round the augite, while in others only a kernel of the original mineral is left, or the whole crystal has been changed. In many cases the altered substance appears as minute needles, blades, and fibres of actinolite. Occasionally, besides the green hornblende, shred-like pieces of a strongly pleochroic brown hornblende make their appearance. Serpentinous and chloritic substances are not infrequent. Epidote is sometimes abundant. The titaniferous iron has commonly passed more or less completely into leucoxene. Here and there a dark mica may be detected.

Some of these features remind us of those which have often been described from zones of contact metamorphism. They no doubt point to the long-continued action of interstitial water, probably at a considerable temperature, and to the mutual reactions of the solutions thus obtained upon the original component minerals of the dolerites and basalts.

(3) *Relation to the Gabbros.*—That the granophyres of Skye, like those of Mull and Rum, invade the gabbros, has been incidentally illustrated in the foregoing part of this Memoir. But as the mutual relations of the two rocks in this island have been the subject of frequent reference in previous writings of geologists, it is desirable to adduce some further evidence from a region which has been regarded as the typical one for this feature in the geological structure of the Inner Hebrides. No geological boundary is more easily traced than that between the pale reddish granophyre and the dark gabbro. It can be followed with the eye up a whole mountain side, and can be examined so closely that again and again the observer can walk or climb for some distance with one foot on each rock. That there should ever have been any doubt about the relations of the two eruptive masses is possibly explicable by the very facility with which their junction can be observed. Their contrasts of form and colour made their boundary over crag and ridge so clear that geologists do not seem to have taken the trouble to follow it out in detail. And as the pale rock undoubtedly underlies the dark, they have assumed this infraposition to mark its earlier appearance.

I will only cite one part of the junction line. It is easily accessible, and the phenomena it displays may be regarded as typical for the whole. It lies in Glen Sligachan immediately to the south of the mouth of Harta Corry. The rounded eminence of Meall Dearg, which rises to the south of the two Black Lochs, belongs to the granophyre, while the rugged ground to the west of it lies in the gabbro. The actual contact between the two rocks can be followed from the side of Harta Corry over the ridge and down into Strath na Creitheach, whence it sweeps northward between the red cone of Ruadh Stac and the black rugged declivities of Garbh Beinn. On Meall Dearg the granophyre becomes fine-grained and even felsitic in texture, and sends into the contiguous gabbro abundant veins, some of which show fine flow-structure. There is no more singular scene in Skye than the lonely tract on the south side of this hill. The ground for some way is nearly level, and strewn with red shingle from the decomposing granophyre underneath. It reminds one of some parts of the desert "Bad lands" of Western America. Grim dark crags of gabbro, streaked with red veins from the granophyre, rise along its western border beyond which tower the black precipices of the Cuillins, while the flaming reddish-yellow cones of Glen Sligachan stand out against the northern sky. The gabbro here includes much fine-grained, sometimes amygdaloidal rock, belonging probably to the plateau-basalts, and sends veins through it, but the veins from the granophyre-mass cross these. An alteration of the basic rocks like that already described may be noticed here. Next the granophyre, they are dull, compact, splintery, shattery, and much veined, and weather with a white crust.

(4) *Relation to the Basic Dykes and Veins.*—In my early paper on the Geology of Strath I pointed out that the "syenite" bosses of Skye cut off most of the basalt-dykes, but are themselves traversed by a few others.* Though I have since been able to confirm and extend this observation, the locality that furnished my original evidence affords in small compass a clearer presentation of the facts than I have elsewhere met with. I then referred to the sections visible at the eastern end of the boss of Beinn an Dubhaich; but similar and even better ones may be cited from the whole northern and southern margins of that eruptive rock. On the north side an extraordinary number of dykes may be traced in the limestone from the shores of Loch Slapin eastwards. They have a general north-westerly trend, but one after another, as I have already remarked, they are abruptly cut off by the granophyre. The latter rock is exposed for nearly a mile in almost continuous section along the shore of Loch Slapin. Yet though I was on the outlook for dykes in it, I found only one. Immediately beyond the eruptive boss, however, they at once appear on either side up to the very edge of the granophyre, where they abruptly cease. The conclusion cannot be resisted that the protrusion of the acid rock took place after most of the dykes of the district had been formed, but before the emission of the very latest dykes which pursue a north-west course across the boss (fig. 54).

Some sections on the southern margin of Beinn an Dubbaich complete the demonstration that such has been the order of appearance of the rocks. Near the head of the Allt Lèth Slighe (or Half-way Burn), where the granophyre sends a long tongue into the limestone, a N.W. basalt dyke is abruptly cut off by the main body of the boss and by the protruded vein (fig. 56). Besides this truncation, the acid rock protrudes strings and threads of its own substance into and across the dyke, these injected portions being as usual of an exceedingly fine felsitic texture.

* *Quart. Jour. Geol. Soc.*, xiv. p. 16.

Similar evidence may be gathered from the area of the great granophyre cones further north. The profusion of basalt-dykes in the surrounding rocks stops short at the margin of that area. The comparatively few dykes which cross the boundary pursue a general N.W. course through the granophyre, and as already remarked, from their dark colour, greater durability and straightness of direction stand out as prominent ribs on the flanks of the pale cones which they traverse.

d. St Kilda.—I have not personally visited this remote island, of which the only geological account we have is that by Macculloch. But through the kindness of my colleague, Mr John Horne, F.R.S.E., I have had a series of specimens submitted to me which were collected by Mr A. Ross of Inverness. These prove that in St Kilda, not only are the rocks of the mountainous parts of Skye and Mull repeated, but that their relative order of appearance is likewise the same. The olivine-gabbros and the granitoid and granophyric rocks are precisely those of the Inner Hebrides. One of the specimens shows a vein of fine granite traversing an ophitic dolerite, and another is a piece of altered fine dolerite or basalt, from near the junction with the acid rocks, and weathers with the white crust so characteristic of similar rocks in the districts above described.

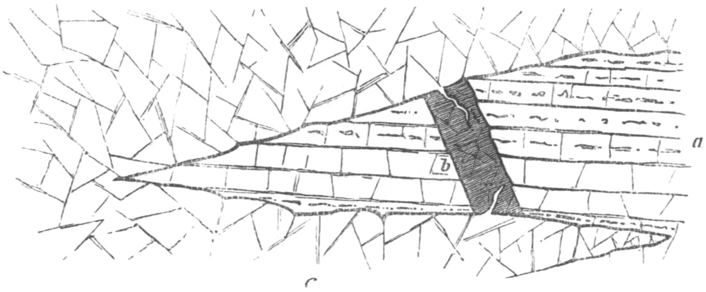


Fig. 56.—Section showing the Truncation of a Basalt Vein (*b*), in Lower Silurian Limestone (*a*), by the Granophyre (*c*) of Beinn na Dubhaich, Skye.

e. Antrim.—In the volcanic region of the north of Ireland the areas of acid rocks are comparatively few in number, and small in size. They nowhere assume the form of prominent hills, and indeed would never attract attention from anything conspicuous in their topography. The largest of them covers a space of about 10 square miles in the heart of the basalt-plateau to the north-east of the town of Antrim, rises to about 1000 feet above the sea, and forms a few featureless hills, some of which are capped with basalt. The best known localities in this tract are Tardree and Carnearny. The rock is chiefly a quartz-trachyte, but here and there pieces of pitchstone and pearlstone may be picked up, which, though I could not find them in place, I have no doubt form part of the main trachyte mass.

Owing to the cover of soil and turf, the junction of this rock with the basalts of the plateau cannot be so clearly seen as in the sections of the Inner Hebrides, and hence the stratigraphical relations of the two groups are apt to be misunderstood. What is actually seen is represented in fig. 57. It has been supposed that the trachyte forms the summit of an ancient volcanic dome that had been erupted and worn down before the outflow of the basalts which gradually accumulated around and over it.* Had this been the true history of the locality, it is inconceivable that of a rock which decays so rapidly as this trachyte, and strews its slopes with such abundance of detritus, not a single fragment should occur between the successive beds of basalt which are supposed to have surrounded and buried it. Though the several beds of basalt are well exposed all round, I could not find a trace of any trachytic fragments between them, nor has Mr SYMES, who mapped the ground in detail for the Geological Survey, been more successful. The basalts near the trachyte are hard and splintery, but not so distinctly altered as round the granophyre in the Inner Hebrides. Were there no other evidence than that furnished by this Antrim locality regarding the relation of the acid and basic rocks of the Tertiary volcanic series of Britain, the question, I admit, could not be satisfactorily settled. But when we compare the Antrim sections with those of the west of Scotland, particularly with those of Mull (figs. 43, 46), we see their close resemblance, and can hardly hesitate to regard the Irish trachyte as later than the basalts around it. For my own part, I have little doubt that the trachytes and pitchstones are not only far younger than the plateau-basalts, but are even later than the granophyres.†

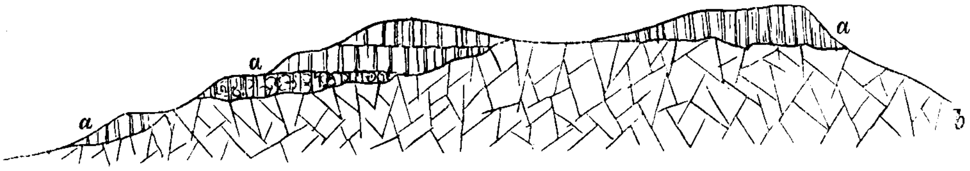


FIG. 57.—Section across the southern slope of Carnearny Hill, Antrim. *aaa*, bedded basalts; *b*, trachyte.

Besides this largest boss of trachyte a number of smaller knobs of trachytic, rhyolitic, perlitic, and vitreous rocks appear at intervals both to the north and south of the Tardree mass, entirely surrounded by basalt. Most of these lie within the area of the lower group of basalts, but one of them to the south-east of Ballymena appears to cross from that group into the upper basalts. These scattered patches, I have no hesitation in believing to be intrusive bosses, sheets, or veins, which, like those of Mull and Skye, have been injected into the basalts long after these rocks had been built up into the plateaux.

* For an early account of the Antrim trachytic rocks, see BERGER, *Trans. Geol. Soc.*, iii. (1816) p. 190. Professor HULL has described the Tardree rock in the Explanation to Sheets 21, 28, and 29, *Geol. Survey of Ireland* (1876), p. 17, and has supposed it to be older than the basalts, referring it to the Eocene period. DUFFIN (quoted by Mr KINAHAN) believed that "the trachytes occur at the centres of eruption, and were probably poured out at the end of the outburst." DU NOYER also (quoted by the same writer) thought them to be newer than the plateau-basalts, and to have lifted up masses of these rocks. Mr KINAHAN himself (*Geology of Ireland*, p. 172) has pointed out the absence of any trachytic fragments between the basalts as an argument against the supposed antiquity of the acid protrusions. A full petrographical account of the Tardree rock is given by VON LASAULX in the paper already cited, Tschermak's *Min. Pet. Mittheil.*, 1878, p. 412.

† [Since this paper was read, and as it is passing through the press, I have received from Mr A. M'HENRY, of the Geological Survey, some interesting information recently obtained by him at Templepatrick, co. Antrim. He has there found what he considers to be conclusive evidence that the trachyte is intrusive in the Lower Basalts; but that it is pierced by younger basic dykes. This is precisely the structure which my experience in the Inner Hebrides would have led me to expect.]

2. *Sills or Sheets.*

Not only have the acid rocks been protruded in huge bosses, they have also been injected in sheets between the bedding planes of stratified rocks, between the surfaces of the basalt-beds, and between the bottom of the plateau-basalts or of the gabbros and the platform of older rock on which the volcanic series has been piled up. Every gradation of size may be observed, from mere partings not more than an inch or two in thickness, up to massive sheets, which now, owing to the removal of their original covering of rock by denudation, form minor groups and ranges of hills. Where the sheets are numerous, they are usually small in size; where, on the other hand, they are few in number, they reach their greatest dimensions.

In Mull they are profusely abundant throughout the central mountainous tract between Loch na Keal and Loch Spelve. If we ascend the slopes from the Sound of Mull, for instance, we have not gone far before some of these sheets make their appearance. They are usually dull granular quartz-porphyries, often only two or three feet in thickness, and interposed between the beds of basalt that form the mass of the hills. Along the crest of the ridge that stretches through Beinn Chreagach Mhor to Mainnir nam Fiadh they take a prominent place among the ledges of basalt, basalt-conglomerate, and dolerite. The largest sheet in Mull is probably that which has thrust itself between the base of the basalts and the underlying Jurassic strata and crystalline-schists on the shore of the Sound of Mull at Craignure. The porphyry of this sheet is referred to by ZIRKEL as only a finer-grained variety of the same quartziferous rock, with hornblende and orthoclase crystals, which in Skye breaks through the Lias.* On the south coast also, at the base of the thick basalt series, similar porphyries have been injected into the underlying strata; and under the great gabbro mass of Ben Buy similar protrusions occur. But as we retire from the mountainous tract into the undisturbed basalts of the plateau, these acid intercalations gradually disappear.

In the islands of Eigg and Rum, excellent examples occur of the tendency which the sheets of porphyry or granophyre manifest to appear at or about the base of the bedded basalts. I have already alluded to the boss or sheet at the north end of the former island. A still more striking illustration occurs in Rum. All along the base of the great mass of gabbro, protrusions of various kinds of acid rock have taken place. The great mass of Orval, already described, is one of these. Below Barkeval and round the foot of the hills to the south-east of that eminence an interrupted band of quartz-porphyry may be traced, from which veins proceed into the gabbros and dolerites.

But it is in Skye and Raasay that the intrusive sheets of the acid group of rocks reach their chief development. They form a band or belt which, though not continuous, can be traced round the east side of the main body of granophyre at a distance of from a mile and a half to about three miles. Beginning near the Point of Suisnish, this belt curves through the hilly ground for some five miles until it dies out on the slopes above

* *Zeitsch. Deutsch. Geol. Gesellsch.*, xxiii. p. 54.

Skulamus. It may be found again on the west side of the ridge of Beinn Suardal and on the moors above Corry till it reaches the shore at the Rudh' an Eireannich (Irishman's Point). It skirts the west side of Scalpa Island, and runs for some miles through Raasay.

Over a large part of its course, the rocks of this belt rest as a great overlying sheet upon the Jurassic strata, which may almost everywhere be seen dipping under them. From the analogy of other districts, we may, I think, infer that their position indicates the intrusion of these sills at the base of the plateau-basalts which have since been removed from almost the whole tract. Fortunately, a portion of the basalts remains in Raasay, and enables us to connect that island with the great plateau of Skye of which it once formed a part. There can be no doubt that the amygdaloidal basalt-beds of the Dun Caan ridge once extended westwards across the band of granophyre which now forms most of the surface between that ridge and the Sound of Raasay. A thin sheet of quartz-porphyry, interposed among the Oolitic strata, may be seen a little inland from the top of the great eastern cliff and below the position of the bedded basalts.

The great sheet, or rather series of sheets, which stretches north-eastwards from Suisnish consists of a rock which for the most part may readily be distinguished in the field from the granitoid material of the bosses. It appears to the naked eye to be a rather close-grained or finely crystalline-granular quartz-porphyry, with scattered blebs or bi-pyramidal crystals of quartz and crystals of orthoclase. At the contact with adjacent rocks, the texture becomes more felsitic, sometimes distinctly spherulitic (W. side of Carn Nathragh, next Lias shale). Under the microscope the rock is seen to be a fine-grained granophyric porphyry or porphyritic granophyre. It caps Carn Dearg (636 feet) above Suisnish, where it covers a space of nearly a square mile, and reaches at its eastern extremity (Beinn Bhuidhe), a height of 908 feet above the sea (fig. 14). This rock rests upon a sill of dolerite, and is apparently split up by it. But, as I have already stated, the basic rock is probably the older of the two, and the granophyre seems to have wedged itself between two earlier doleritic sheets. To the north-west of Carn Dearg, above the northern end of the crofts of Suisnish, the same sill, or one occupying a similar position, crops out between masses of granophyre, and is intersected by narrow veins from that rock.

Though severed by denudation, the large sheets of granophyre to the east of Beinn Bhuidhe are no doubt continuations of the Carn Dearg mass, or at least occupy a similar position. That they are completely unconformable to the Jurassic rock is shown by the fact, that while at Suisnish they lie on sandstones which must be fully 1000 feet above the bottom of the Lias, only two miles to the east they are found resting on the very basement limestones within a few yards from the underlying quartzite and Cambrian sandstone. I do not think that this transgression can be accounted for by intrusion obliquely across the stratification. I regard it as arising from the eruptive rock having forced its way between the bottom of the now vanished basalt-plateau and the denuded surface of Jurassic rocks, over which the basalts were poured. The platform underneath these granophyre sills thus represents, in my opinion, the terrestrial surface before the beginning of the volcanic period.

But there is abundant proof that though the intruded granophyre sills followed generally this plane of separation, they did not rigidly adhere to it, but burrowed, as it were, along lower horizons. Thus on the south-east front of Beinn a' Chàirn, which forms so fine an escarpment above the valley of Heast, the base of the granophyre, after creeping upward across successive beds of limestone, sends out a narrow tongue into these strata,

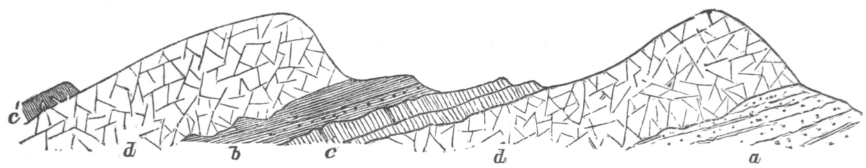


Fig. 58.—Section across the Granophyre Sills at Loch a' Mhullaich, above Skulamus, Skye. *a*, Jurassic sandstones and shales; *b*, Jurassic dark brown sandy shales; *c*, sills of basalt, some bands highly cellular; c^1, basalt-sill with veins of felsite rising into it from the granophyre below; *dd*, intrusive sheets or sills of granophyre.

and continues its course a little higher up in the Lias. The same rock, after spreading out into the broad flat tableland of Beinn a' Chàirn (983 feet), rapidly contracts north-eastwards into a narrow strip which forms the crest of the ridge, and at once suggests a much weathered lava-stream. The resemblance to a *coulée* is heightened by the curious thinning off of the rocks where the two streams emerge from the Heast lochs; it looks as if the igneous mass were a mere superficial ridge which had been cut down by erosion, so as to expose the shales beneath it. But that the granophyre is really a sill becomes abun-

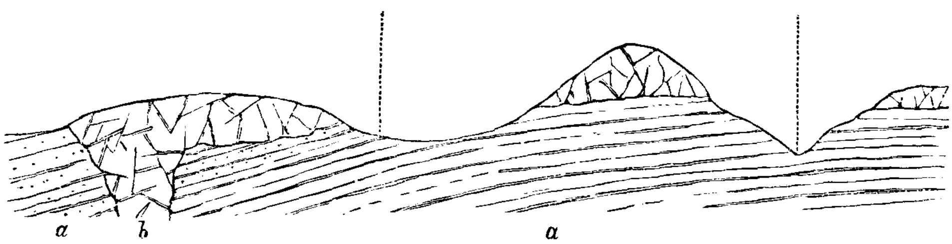


Fig. 59.—Section to show the connection of a Sill of Granophyre with its funnel of supply, Raasay. *aa*, Jurassic sandstones; *b*, granophyre.

dantly clear at its eastern end, where we find that it consists of two separate sheets with intervening Liassic shales. The structure of this interesting locality is shown in fig. 58. In this instance also, there is evidence that the acid sills are younger than the basic, for the upper sheet of granophyre sends up into the overlying dark basaltic rock narrow vertical felsitic veins, a quarter of an inch to an inch in width, which being more durable, stand out above the decomposable surface of the containing rock, and show their quartz-blebs and felspar crystals on the weathered surface.

It is not easy to determine where lay the vent or vents from which these granophyre sills in Skye proceeded. Possibly they may be concealed underneath some of the larger areas of the rock, such as those of Carn Dearg or Beinn a' Chàirn. In Raasay, however, it is possible to connect the sheets with the funnels through which they ascended. This is well seen near the Manse, where the accompanying section may be observed (fig. 59). Owing to great denudation, the massive sheet of granophyre has been cut into isolated outliers which cap the low hills, and the rock may be seen descending through the Jurassic sandstones, which in places are much indurated. It is observable that the amount of contact metamorphism induced by the granophyre sills upon the rocks between which they have been injected is comparatively trifling. It is for the most part a mere induration, sometimes accompanied with distortion and fracture.

3. *Veins and Dykes.*

Besides bosses and sills, the acid rocks of the Inner Hebrides take the form of veins and dykes which have invaded the other members of the volcanic series. Some of these have already been referred to; but a more particular description of the venous development of the acid rocks as a whole is now required.

Considered as a petrographical group, these veins and dykes are marked by the following characters. At the one extreme we have thoroughly vitreous rocks in the pitchstones. Among these, however, various degrees of devitrification appear, leading us to the completely devitrified felsites, which occur almost entirely as veins or dykes. Occasionally the microgránitic structure makes its appearance. More frequently, however, the veins and dykes consist of what macroscopically are quartz-porphyries, and which under the microscope can generally be resolved into granophyric porphyries or true granophyres. In a few instances, the veins proceeding from the granitic bosses show a granitic structure.

In their mode of occurrence, the smaller protrusions of acid rocks differ considerably from the ordinary type of the dykes and veins of the basic group. They comparatively seldom form true dykes. Most frequently they occur as irregular veins, which vary much within a short space in thickness and direction. They never exhibit the persistent trend and parallelism of opposite walls, so distinctive of the basic dykes. The phenomena attending their eruption must have been correspondingly different. Their advent was not preceded by the rending of the terrestrial crust into long parallel fissures. On the contrary, they seem to have been forced between the irregular rents, joints, and bedding-planes of the rocks, so that they often pursue a singularly sinuous course.

Round the margin of the larger granophyre bosses, veins have sometimes been given off in great numbers, as has been stated above. But, for considerable distances, not a single vein or dyke may appear. Along the well-exposed boundary of Beinn-an-Dubhaich, for example, though the edge of the granophyre is remarkably notched, there are hardly any protrusions that deserve the name of veins. In the central mountainous tract of Mull, veins of various porphyries and felsitic rocks are extraordinarily abundant.

They appear not so much at the actual margins of the bosses (though they occur there, as has already been described), as in that tract of altered basalt, with intrusive sheets and dykes of basalt, dolerite, and gabbro, which lies within the great ring of heights between Loch-na-Keal and Loch Spelve. In some areas the amount of injected material appears to equal the mass of basic rock into which it has been thrust. Pale grey and yellowish porphyries and granophyres, varying from thick dykes down to the merest threads, ramify in an intricate network through the dark rocks of the hills, as shown in the accompanying illustration (fig. 60), which represents a portion of the hill-side between Beinn Fhada and the Clachaig River. Such a profusion of veins probably indicates the existence here of some large mass of granophyre, or of granite at no great depth beneath the surface.

There are two horizons on which, as I have already had occasion to point out, protrusions of acid materials have been specially abundant. One of these is the base of

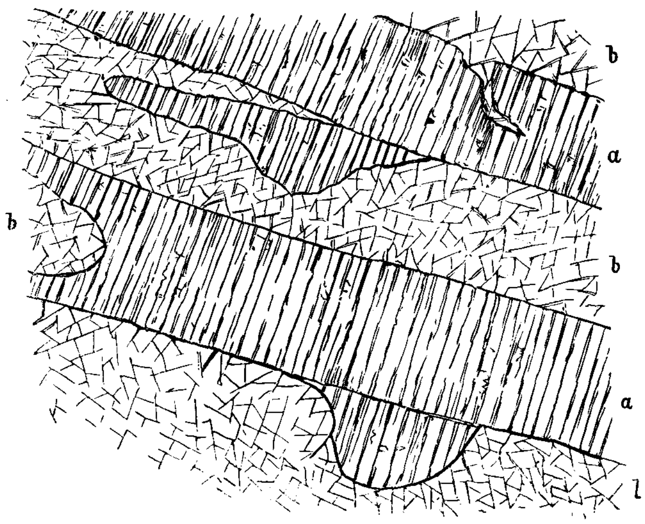


FIG. 60.—Section of Intruded Veins of various Acid Rocks (*bb*), in Basalt, Dolerite, &c. (*aa*), above River Clachaig, Mull.

the bedded basalts of the plateau; the other is the bottom of the thick sheets of gabbro. Dykes and veins of granophyre, quartz-porphyry, felsite, and other allied rocks are sometimes crowded together along these two horizons, though they may be infrequent above or below them. But examples also occur of solitary veins in the midst of the unaltered plateau-basalts, at some distance from the nearest visible body of acid eruptive rock. Some of the most remarkable instances of this kind are to be seen among the basalts that form the terraced slopes on the north side of Loch Sligachan. Several thick dykes of granophyre run up the declivity, cutting across hundreds of feet of the nearly level basalt beds. Some of them can be seen on the shore passing under the sea. They trend in a S.S.E. direction towards Glamaig, and they are not improbably apophyses from that huge boss. Another example may be cited from the basalt-outlier of Strathaird, where two veins of felsite, one of them a pale flinty rock showing flow-structure parallel to the walls, may be seen on the west front of Ben Meabost. In this case, the veins are three miles and a half from the granophyre mass of Strath-na-Creitheach to the north, four miles from that of Beinn-an-Dubhaich to the north-east, and nearly three miles from that of Coire Uaigneich at the foot of Blath Bheinn.

A special place must be reserved for the pitchstone-veins. Ever since the early explorations of JAMESON and MACCULLOCH, the west of Scotland has been noted as one of the chief European districts for these vitreous rocks. From Skye to Arran, and thence to Antrim, many localities have furnished examples of them, but always within the limits of the Tertiary volcanic region. That all of the pitchstones are of Tertiary age cannot, of course, be proved, for some of them are found traversing only Palæozoic rocks, and of these all that can be absolutely affirmed is that they must be younger than the lower part of the Carboniferous system. But, as most of them are unquestionably parts of the Tertiary volcanic series, they are probably all referable to that series. Not only so, but there is, I think, good reason to place them among its very youngest members. It is a significant fact that they almost always occur either in or close to granophyre bosses, the comparatively late origin of which has now been proved. The first pitchstone observed in Skye was found by JAMESON on the flanks of the great granophyre cone of Glamaig. Another rises on the side of the porphyry mass of Glas Bheinn Bheag, in Strath Beg. A third occurs at the foot of Beinn-na-Caillich. In Rum, I found a pitchstone vein traversing the western slopes of the wide granophyre boss of Orval. In Eigg, the well-known veins of this rock intersect the plateau-basalts, but in their near neighbourhood lie the masses of quartz-porphyry already alluded to. In Ardnamurchan also, the pitchstone has been injected into the plateau-basalts, but there are many small veins of close-grained felsitic or rhyolitic rocks in the vicinity. In Antrim, pitchstone occurs in the midst of the trachyte of Tardree. The only marked exceptions to the general rule, with which I am acquainted, are those of the island of Arran. Most of the pitchstone-veins in that district traverse the red sandstones which lie at the base of the Carboniferous system, or belong to the Old Red Sandstone. But none of them are far removed from the great granite boss of the northern half of the island, while large masses of quartz-porphyry, which strikingly resemble some of those of Skye and Mull, lie still nearer to them. It is also worthy of notice that pitchstone-veins rise through the granite boss itself, the probably Tertiary date of which has been already referred to.

FIG. 61.—Pitchstone Vein traversing the Bedded Basalts, Rudh an Tangairt, Eigg.

This common association of pitchstone-veins with the Tertiary eruptive bosses of acid rocks can hardly be a mere accidental coincidence. It seems to me to prove a renewed extravasation of acid material, now in vitreous form, from the same vents that had supplied the granitoid, granophyric, porphyritic, and felsitic varieties of earlier protrusions. We must remember that the pitchstone-veins are not mere local glassy parts of the larger bodies of granophyre or felsite in or near which they lie. Their margins are sharply defined; they are indeed in all respects as manifestly intruded, and therefore later masses, as are the basalt-dykes. Their occurrence, therefore, within the granophyre bosses proves them to be younger than the youngest of the large erupted masses of the Tertiary volcanic series. Whether they are also later than the latest basalt-dykes cannot yet be decided, for I have never succeeded in finding an example of the intersection of these two groups of veins and dykes. But, with this possible exception, the pitchstones are the most recent of all the eruptive rocks of Britain. This fact acquires additional interest when taken in connection with the history of the Scuir of Eigg, to be immediately referred to.

As a rule, the intrusive pitchstones occur as veins which cannot be traced far, and which vary from a few yards to less than an inch in width. They generally show considerable irregularity in breadth and direction, sometimes sending out strings into the surrounding rock (fig. 61). The outer portions are not infrequently more glassy and obsidian-like than the interior. Occasionally the vitreous character disappears by devitrification, and the rock assumes the texture of a compact felsite or of a spherulite-rock.*

4. *Superficial Lava Streams.*

The question whether any of the acid volcanic rocks were actually emitted at the surface, fortunately does not rest in the uncertainty in which we are compelled to leave the same question when asked of the bosses of gabbro, but admits of a positive answer. One solitary example remains of a true superficial stream of acid lava—that of the Scuir of Eigg. But when we consider the form of the granophyre cones, as already described, the indication of an internal structure in some of them, corresponding more or less with their external form, and the occasional presence of brecciated portions along their margins, it is difficult to believe that no connection was established between these cones and the outer air. Although no "lava," using that word in VON BUCH's comprehensive sense of anything that flows from a volcanic orifice, may have spread outwards from the necks of granophyre, the molten material may have been protruded to the daylight in some such form as the domite puys of Auvergne. A comparatively small amount of denudation would suffice to efface any evidence that the igneous rock had ever reached the surface. But, in actual fact, the denudation has been enormous. Not a single vestige now remains of a superficial discharge from any one of the numerous granophyre cones of Skye.

The solitary remnant of an acid lava-stream, forming the conspicuous Scuir of Eigg, has already been fully described by me, and for its structure and history I must refer to a former paper,† contenting myself here with a brief summary, and with a statement of

* For an account of the pitchstone veins of Eigg, see *Quart. Jour. Geol. Soc.*, xxvii. p. 299.

† *Quart. Jour. Geol. Soc.*, xxvii. (1871) p. 303.

new facts and inferences, obtained from a recent re-examination of the locality. The general form of the ridge of the Scuir will be understood from the accompanying map of the island of Eigg (fig. 62). The length of the ridge is two miles and a quarter, its greatest breadth 1520 feet, its extreme height 1289 feet. It consists of successive sheets of columnar porphyritic pitchstone, and of a dull grey devitrified felsitic rock, the whole

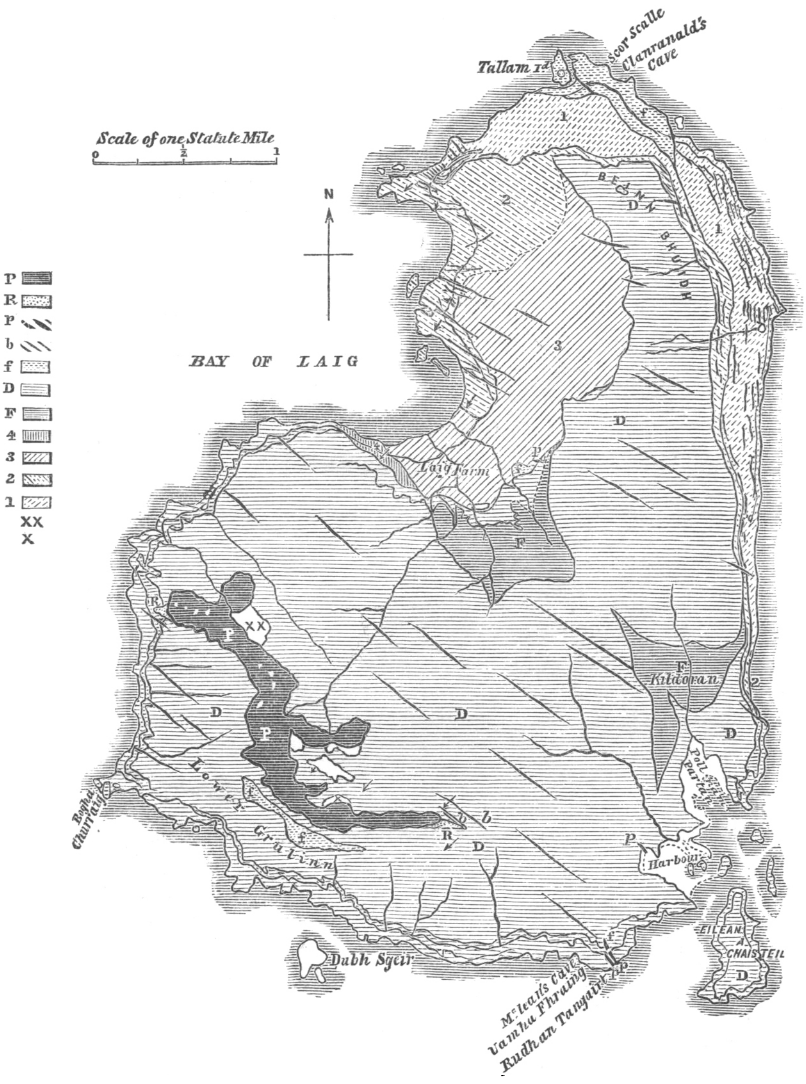


FIG. 62.—Geological Map of the Island of Eigg. P, Pitchstone of Scuir ; R, old river gravel under pitchstone ; *pp*, small veins of Pitchstone; *bb*, dykes, veins and sheets of intrusive basalt; the short black lines running N.W. and S.E. are basalt dykes ; *ff*, granophyre sills; D, bedded basalts with occasional tuffs; F, sheet of the " pale group " of Mull; 1, 2, 3, 4, clays, shales, sandstones, limestones, &c. (Jurassic) ; xx, Loch Beinn Tighe ; x, Loch a Bhealaich. ➤→ General dip of the rocks.

having a united thickness of several hundred feet. Examined in thin sections under the microscope, the vitreous beds present a pale brown glass, with abundant depolarising microlites, large porphyritic crystals of sanidine, sometimes plagioclase, and smaller crystals of augite and magnetite. Some of these beds have only a feebly resinous lustre, and resemble in some respects andesites. In one of the slides the porphyritic felspars are chiefly plagioclase. The dull grey felsitic bands show under the microscope a more thoroughly devitrified ground-mass, with the minutest depolarising microlites, large porphyritic crystals of plagioclase and sanidine, grains of augite, and sometimes exceedingly abundant particles of magnetite.

That the rocks of the Scuir of Eigg are the products of several eruptions is manifest from their arrangement in distinct beds, and from their variation in petrographical character, and that they were poured into the channel of a stream which had been eroded out of the surface of the plateau-basalts, is proved by the survival of the shingle and drift wood of that channel below the bottom of the pitchstone. The general relations of the rocks are impressively presented on the west side of the island, where the rock of the Scuir is abruptly cut off by the face of the sea-precipice, which is some 500 feet high (fig. 63).

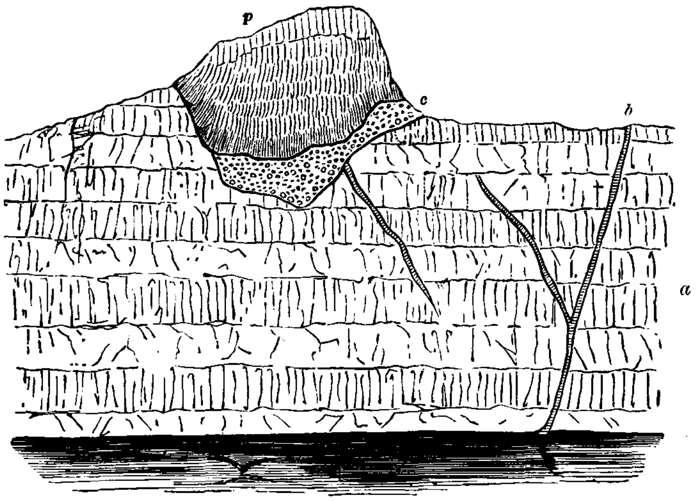


FIG. 63.—Natural Section of the Sea-cliff at the south-west end of the ridge of the Scuir of Eigg. *a*, Bedded basalts of the plateau; *b*, basic dykes; *c*, gravel of old river-bed; *p*, Pitchstone of the Scuir.

At both ends of the pitchstone ridge, we learn that the dykes of fine-grained basalt which traverse the bedded basalts, are older than the ancient Tertiary river-bed of the Scuir, for the river has not only eroded the bedded basalts but has cut down into the dykes. There is thus evidence of enormous denudation of the surface of the basalt-plateau before the final volcanic outbursts, and of the comparatively late date of the pitchstone.

The sinuous ridge of the Scuir still marks the winding course of the stream whose channel the pitchstone effectually sealed up and preserved. Several minor spurs, which project from the eastern side of the main ridge, show the positions of small tributary rivulets that entered the principal channel from the slopes of the basaltic tableland. One of these, on the south-east side of Corven, must have been a gully in the basalt with a rapid or waterfall. The pitchstone has flowed into it, and some of the rounded pebbles that lay in the channel of this vanished brook may still be gathered where the degradation of the pitchstone has once more exposed them to the light.

In trying to reconstruct the topography of the ground, at the time when the streams of pitchstone flowed, there are several little pieces of evidence which help us. Among the water-worn blocks of the buried river-bed, which are wrapped up in a gravel of basalt débris, there occur fragments of the volcanic rocks of the plateau, also of red (Cambrian) sandstone, quartzite, clay-slate, and white (Jurassic) sandstone. All these rocks are found in place at higher elevations to the north, but in no other direction. There is therefore good reason to suppose that the river drained some wooded region lying to the north of the present island of Eigg, of which the red sandstone mountains of Ross-shire, the white sandstone cliffs of Skye and Raasay, and the quartzite and slate uplands of western Inverness-shire are surviving fragments. That the stream, in that portion of its channel preserved under the Scuir, flowed from east to west, may be inferred from the angle at which the tributaries meet the main stream, and also from the fact that the old river-bed at the east end of the Scuir is considerably higher than at the west end.

The direction of the flow of the stream may afford some indication of that of the pitchstone currents. There can be little doubt, I think, that the lava flowed down the river-valley. Its successive streams are still inclined from east to west. The vent of eruption, therefore, ought to be looked for, not towards the west, but towards the east. Nowhere within the Tertiary volcanic region is there any boss of pitchstone or any mass the shape or size of which is suggestive of an actual vent of discharge to the surface. In the island of Eigg no boss of any kind exists, save those of granophyric porphyry already referred to. But none of these affords any satisfactory links of connection with the rock of the Scuir. More probably the vent lay somewhere to the east on ground now overflowed by the sea. The pitchstone veins of Eigg may represent some of the subterranean extrusions from the same volcanic pipe, and, if so, its site could not be far off. But no other relic of its activity now remains. The lofty picturesque ridge of the Scuir, now so prominent an object in the West Highlands, once occupied the bottom of a valley worn out of the basaltic tableland. Prolonged and stupendous denudation has destroyed the connection with its source, has cut down its ends into beetling precipices, has reduced the former surrounding hills into gentle slopes and undulating lowland, and has turned the bottom of the ancient valley into a long, narrow, and high crest. In this worn fragment we see the only evidence which now remains, that towards the close of the protracted volcanic history of the Tertiary period, streams of acid lavas flowed out over the wasted surface of the basalt-plateaux.

V. SUMMARY.

In this final section of the paper, I shall briefly sketch what seem to me to have been the leading features in the history of Tertiary volcanic action in the British Islands.

1. The region within which this activity manifested itself, during Tertiary time in Britain, cannot be very strictly defined, but if it is restricted to those parts of the country where igneous rocks, probably of that age, now appear at the surface, we find that it

includes the north of England and of Ireland, the southern half and the west coast of Scotland—a total area of more than 40,000 square miles. Over that extensive region volcanic phenomena were displayed during an enormously protracted interval of geological time. The earliest beginnings of disturbance may possibly go back into the Eocene period, and the final manifestations may not have ceased until the Miocene, or even perhaps later. So protracted was the duration of the eruptions, that there was room for enormous topographical changes from denudation, and also for considerable variation in the fauna and flora, alike of land and sea.

2. Owing to some cause which has not yet in this relation been investigated, but which is probably referable to secular terrestrial contraction, the volcanic region underwent elevation, while, at the same time, a vast subterranean lake or sea of molten rock appeared underneath it. Enormous horizontal tension thus arose, and at last the stretched terrestrial crust gave way. A system of approximately parallel fissures opened in it, having a general direction towards N.W. The rapid and simultaneous production of such a gigantic series of rents must have given rise to earthquakes of enormous magnitude and destructive force. The great majority of the fractures, doubtless, did not reach to the surface of the ground, though probably not a few did so. Such was the potency of this development of terrestrial energy, that the fissures ran through the most varied kinds of rocks and the most complicated geological structures, crossing even earlier lines of powerful dislocation, and yet retaining their direction and parallelism for sometimes 50 or 100 miles.

3. No sooner were the fissures formed than the molten lava underneath was forced upward into them for many hundreds or even thousands of feet above the surface of the subterranean lava-sea. Solidifying between the fissure walls, it formed the crowd of basic dykes that stands out as the most widespread and distinctive feature of the volcanic region.

4. Where the fissures reached the surface or near to it, the molten rock would seek relief by egress in streams of lava. This probably occurred in many places from which subsequent denudation has removed all vestige of superficial volcanic manifestations. But, in the great range of basalt-plateaux, from Antrim through the chain of the Inner Hebrides, there are still left abundant remains of the surface outflows. After the convulsions ceased which produced the dykes, the communication that had been established between the reservoir of molten rock underneath and the upper air would be maintained, and repeated eruptions might take place either from the original vents or from others afterwards opened by the volcanic energy.

5. For a prolonged geological period, various basic lavas (basalts, dolerites, &c.) continued to flow out from innumerable vents until they had filled up the hollows of the great valley, which then stretched from the south of Antrim northwards between the west coast of Scotland and the chain of the Outer Hebrides. In some places, the accumulated pile of such ejections even now exceeds three thousand feet, and yet we cannot tell how much material has been bared away from its top by denudation. The surface over which the lava flowed seems to have been mainly terrestrial. Here and there,

between the successive sheets of basalt, the leaves, stems, and fruit of land-plants, sometimes in most perfect preservation, may be observed, together with the remains of insects. It is remarkable that the volcanic discharges consisted mostly of lava. Fragmentary materials were comparatively insignificant in amount, and local in origin, though layers of fine tuff and basalt-breccias occur in all the plateaux. Neither these materials nor the lavas thicken towards any centres that might be taken to mark volcanoes of the type of Vesuvius or Etna. On the contrary, the persistent flatness and uniformity of the volcanic series, and the thinning out of the separate beds in different directions, point to the existence of many minor vents from which the discharges took place. The positions of not a few of these vents can still be ascertained. They are now filled sometimes with dolerite, sometimes with coarse agglomerate. As the pile of erupted volcanic materials of the plateaux gradually thickened, and the subterranean energy grew feebler, the ascending lava, instead of rising to the surface, was forced between the layers of sedimentary strata underneath or between these and the overlying basalts, so as to form intrusive sheets or sills.

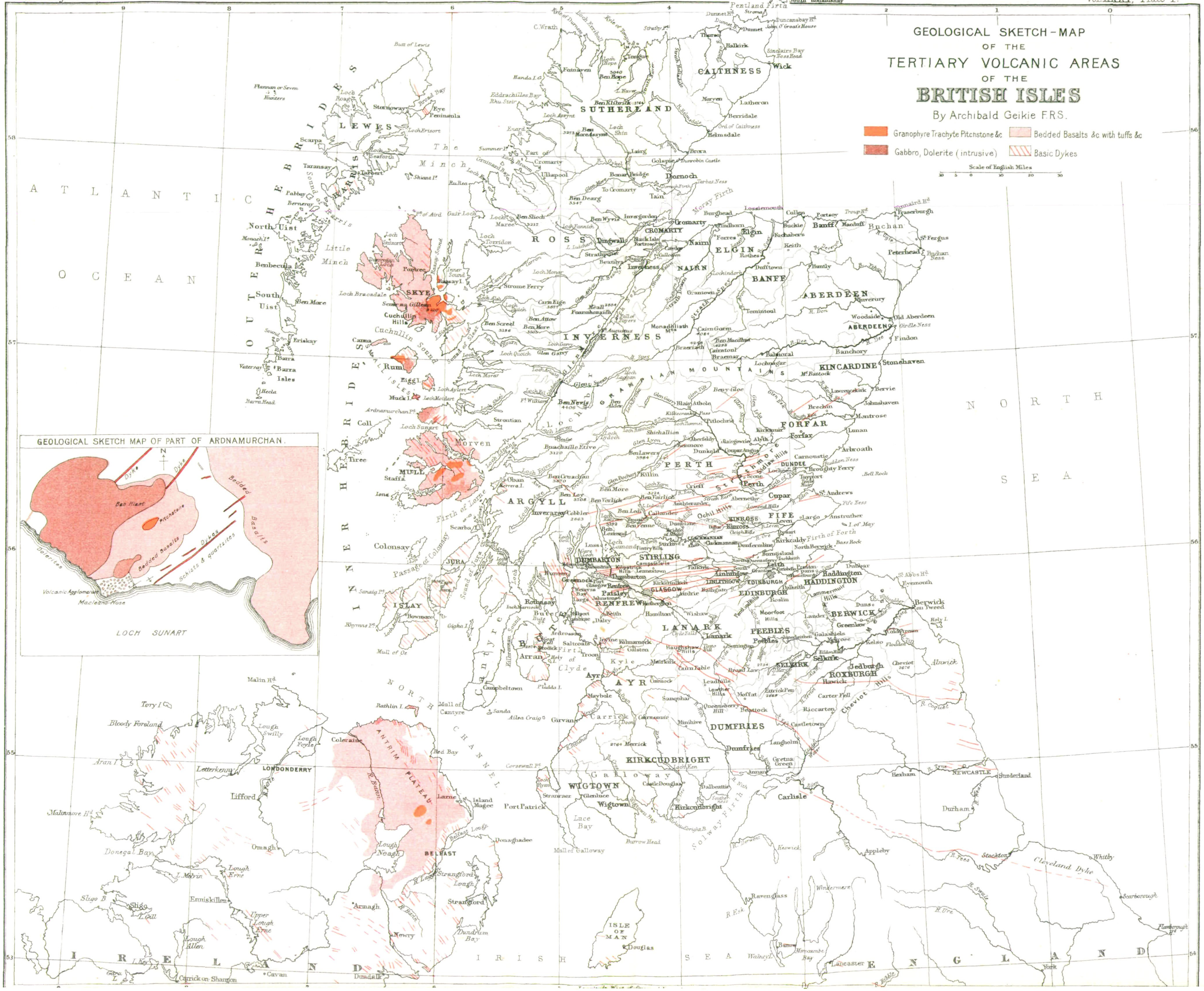
6. When the great plateaux of basalt had been built up to a thickness of several thousand feet, another remarkable episode in the volcanic history occurred. This consisted in the uprise at certain points of coarsely crystalline basic rocks, which ultimately solidified as dolerites, gabbros, troctolites, picrites, &c. There is reason to believe that the points of extravasation of these materials were mainly determined by the positions of the larger or more closely clustered vents of the plateau-period, where lines of weakness consequently existed in the terrestrial crust. Rising as huge bosses through such weak places, the gabbros and associated rocks raised up the overlying bedded basalts, and forced themselves between them, forming thus a fringe of finer-grained intrusive sills and veins around the central amorphous cores of more coarsely crystalline material. Whether, in any of these vast domes of upheaval, the summit was disrupted, so as to allow the basic intrusion to flow out as lava at the surface, cannot now be told, owing to enormous subsequent denudation.

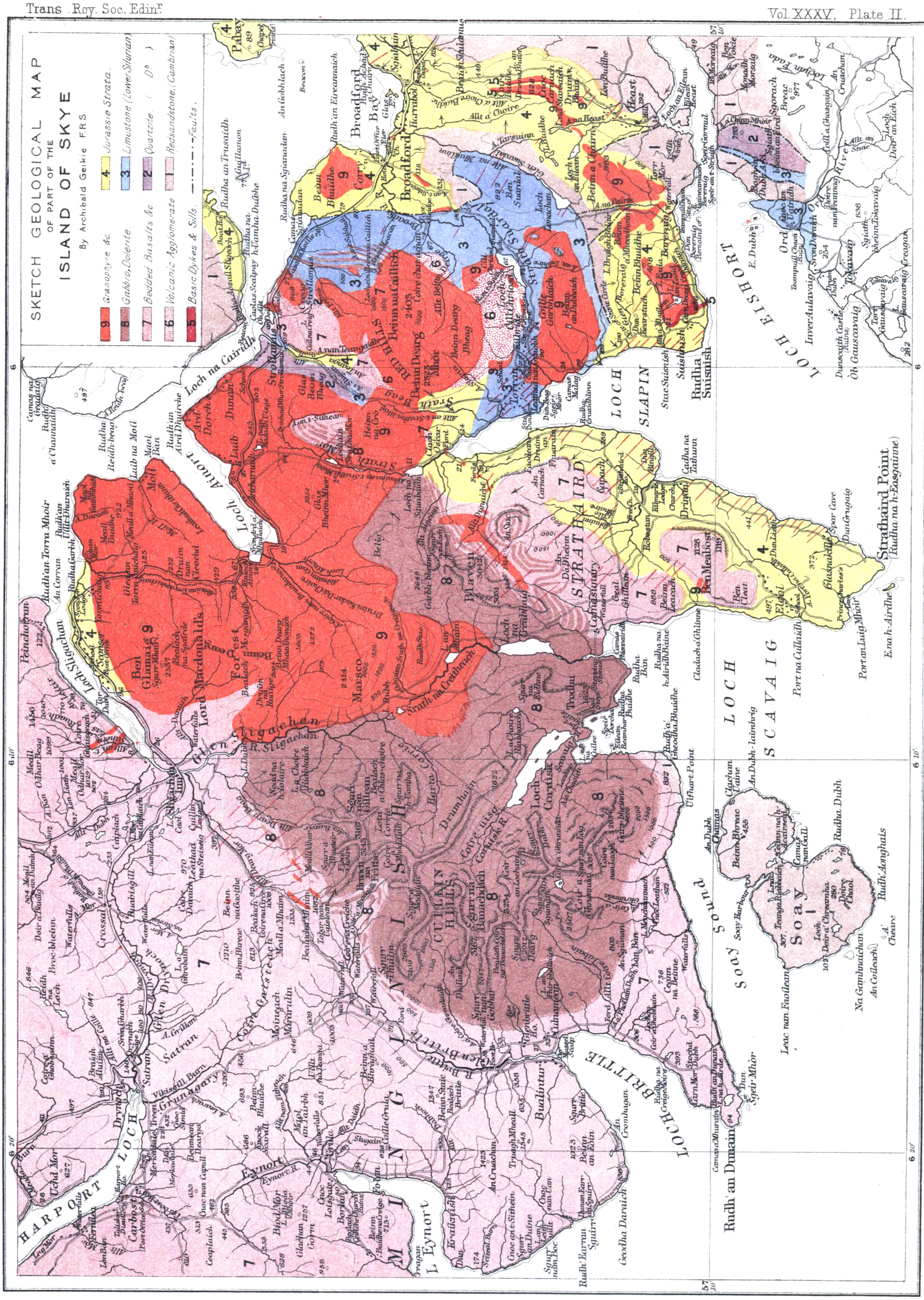
7. The next chapter in the chronicle shows us that probably long after the eruption of the gabbros, when possibly all outward symptom of volcanic action had ceased, a renewed outbreak of subterranean activity gave rise to the protrusion of another and wholly different class of materials. This time the rocks were of a markedly acid type. They included varieties that range from dark flinty felsites through porphyries and granophyres into compounds which cannot be classed under any other name than granite. These masses likewise availed themselves of older vents in the plateaux, and broke through them. They now form huge conical hills, which, in their outer aspect, and even to some extent in their inner structure, recall the trachytic *puys* of Auvergne. But the granophyres not only ascended through the basalt-plateaux and the gabbro-bosses; they sent into these rocks a network of veins, and pushed their way in huge sheets or sills between the strata below. Around the bosses of gabbro and granophyre, the bedded basalts have undergone considerable contact-metamorphism.

8. The gabbro and granophyre bosses of the Inner Hebrides demonstrate with singular force how unreliable petrographical characters are as a test of the relative age of rocks. No one looking at hand-specimens of these rocks, or even studying them in the field, would at first suspect them to be of Tertiary date. They precisely resemble rocks of similar kinds in Palæozoic and even Archæan formations. Yet, of their late appearance in geological time, there cannot be any possibility of doubt.

9. After the uprise of the granophyre, and the injection of the network of felsitic veins, there came once more a period of terrestrial convulsion like that of the earliest basic dykes, but of less intensity. Again, the crust of the earth over the volcanic region was pushed upward and rent open by another system of parallel fissures, directed in a general N.N.W. line. Again, from a sea of basic lava underneath, molten rock was forced upwards into the rents, and thus another system of basic dykes was formed. These dykes are found crossing those of earlier date, and rising through the other volcanic rocks. They traverse the plateau-basalts from bottom to top; they climb to the summits of the gabbro mountains, and they even pursue their undeviating course over the huge domes of granophyre. No proof has yet been found that from any of these dykes there was a superficial outflow of lava. But so great has been the subsequent denudation of the areas, that such outflows might quite well have taken place, and have subsequently been destroyed.

10. Whether these basic dykes were the last manifestation of volcanic energy in our region cannot yet be decidedly affirmed. But, so far as the evidence at present goes, they are possibly older than another series of veins and dykes, consisting chiefly of pitchstone, which are found at many points from Antrim to the far end of the Inner Hebrides. These vitreous protrusions traverse every other member of the volcanic series, and do not appear to be themselves cut by any. At one locality, the Scuir of Eigg, they reached the surface, and flowed out in streams of molten rock over the basalt-plateau, which had now been deeply trenched into valleys and ravines by running water. The singularly durable pitchstone, flowing into a river-bed, has thus preserved an impressive memorial of the vanished topography of Tertiary time, and of the enormous duration of the Tertiary volcanic period in the geological history of the British Isles.


GEOLOGICAL SKETCH-MAP
OF THE
TERTIARY VOLCANIC AREAS
OF THE
BRITISH ISLES
By Archibald Geikie F.R.S.
Granophyre Trachyte Pitchstone &c
Gabbro, Dolerite (intrusive)
Bedded Basalts &c with tuffs &c
Basic Dykes
Scale of English Miles
GEOLOGICAL SKETCH MAP OF PART OF ARDNAMURCHAN.
Ben Hiant
Pitchstone
Bedded Basalts
Dykes
Schists & quartzites
Basalts
Dolerites
Volcanic Agglomerate
Maclean's Nose
LOCH SUNART
ATLANTIC OCEAN
NORTH SEA
OUTER HEBRIDES
INNER HEBRIDES
SUTHERLAND
CAITHNESS
ROSS
INVERNESS
ARGYLL
PERTH
FORFAR
ABERDEEN
BANFF
ELGIN
NAIRN
KINCARDINE
FIFE
STIRLING
DUMBARTON
RENFREW
LANARK
EDINBURGH
HADDINGTON
BERWICK
PEEBLES
SELKIRK
ROXBURGH
AYR
DUMFRIES
KIRKCUDBRIGHT
WIGTOWN
SKYE
MULL
ISLAY
JURA
ANTRIM PLATEAU
BELFAST
LONDONDERRY
ISLE OF MAN
IRELAND
ENGLAND
IRISH SEA
NORTH CHANNEL
GRAMPIAN MOUNTAINS
Cleveland Dyke


SKETCH GEOLOGICAL MAP
OF PART OF THE
ISLAND OF SKYE
By Archibald Geikie F.R.S.
9 Granophyre &c.
8 Gabbro, Dolerite
7 Bedded Basalts &c.
6 Volcanic Agglomerate.
5 Basic Dykes & Sills.
4 Jurassic Strata.
3 Limestone (Lower Silurian)
2 Quartzite (Do)
1 Redsandstone (Cambrian)
Faults.
John Bartholomew & Co., Edin.r