ON THE

CARBONIFEROUS VOLCANIC ROCKS

OF THE

BASIN OF THE FIRTH OF FORTH:

THEIR STRUCTURE IN THE FIELD AND UNDER THE MICROSCOPE

BY

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XII.—*On the Carboniferous Volcanic Rocks of the Basin of the Firth of Forth —their Structure in the Field and under the Microscope.* By Professor Geikie, LL.D., F.R.S., Director of the Geological Survey of Scotland. (Plates IX., X., XI., XII.)

(Read 3d February and 2d June 1879.)

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Introduction.

The geographical area embraced in the present memoir forms a well-marked basin traversed along its centre by the estuary of the Forth. It is bounded on the north by the chain of the Ochil Hills, on the south by the range of the Pentland and Lammermuir uplands. Towards the west it joins along a low watershed the basin of the Clyde, while eastwards it dips under the waters of the North Sea. Within this defined space the Carboniferous rocks occupy what may be described as one great synclinal trough, varied by innumerable smaller synclines and anticlines. Save where cut out by powerful dislocations, their lower members rise up along the margins of the basin, while their highest portions cover a smaller area in the centre. The older formations forming the northern and southern boundaries of the area belong chiefly to the Lower Old Red Sandstone, in the Lammermuir district to the Lower Silurian. The Carboniferous rocks everywhere rest upon them unconformably.

Within the region thus limited the Carboniferous system in its Scottish type is admirably displayed in numerous natural and artificial sections. Every great group of strata can be satisfactorily examined, and thus a thorough knowledge can be obtained of the detailed stratigraphy. One of the most noteworthy features in the geological structure of this part of Scotland is the abundance and variety of the volcanic rocks associated with the older half of the Carboniferous system. For a protracted geological period the site of the present basin of the Firth of Forth was occupied by numerous volcanic vents, emitting showers of tuff and streams of lava, which were duly interstratified with the contemporaneous sediments. A record has thus been preserved of a remarkable phase of palæozoic volcanic activity. Affording means of comparison with Tertiary and modern volcanic phenomena, down even into many points of minute detail, it enables us to decide whether volcanic action was essentially different in early geological times from its present conditions. Traces of the influence of WERNER's doctrines regarding the modern and abnormal character of volcanic action may be detected even yet in modern geological literature. It has seemed to me that a useful end might be served by subjecting the well-developed volcanic series in the Carboniferous system of the Forth district to rigid scrutiny in the field and detailed study with the microscope. The results of this investigation I now lay before the Society.

From the number and variety of the natural sections near Edinburgh the igneous rocks of this region have been the subject of numerous observations from the early days of geology down to the present time. The mere enumeration of the titles of the various publications on the subject would form a long list. As I shall have occasion elsewhere to refer to these various papers, it will be sufficient at present to point out that the igneous rocks of the Edinburgh district have afforded materials for some well-known researches in theoretical and structural geology, and to allude to a few of the more important descriptions of them. These rocks formed the subject of some of HUTTON's early observations, and furnished him with the facts from which he established the igneous origin of "whinstone."* They supplied PLAYFAIR with numerous apt illustrations in support of HUTTON's views, and he seems to have made himself thoroughly familiar with them.† In the hands of Sir JAMES HALL they formed the groundwork of those remarkable experiments on the fusion of whinstone which may be said to have laid the foundation of experimental geology.‡ In the controversies of the Neptunian and Plutonian schools these rocks were frequently appealed to by each side in confirmation of their respective dogmas. The appointment in 1804 of JAMESON to the Chair of Natural History in the Edinburgh University gave increased impetus to the study of the igneous rocks of this region. Though he did not himself publish much regarding them, we know that he was constantly in the habit of conducting his class to the hills, ravines, and quarries of the neighbourhood, and that the views which he taught were imbibed and extended by his pupils.§ Among the early writers the names of ALLAN,‖ TOWNSON,¶ and Lord GREENOCK,** deserve especial mention.

The first broad general sketch of the igneous rocks of the basin of the Forth was that given by HAY CUNNINGHAM in his valuable Essay on the Geology of the Lothians.†† He separates these rocks into two series, the Felspathic, including porphyry and clinkstone, and the Augitic or Trap rocks. To these he adds Trap-tufa, and considers it identical in origin with modern volcanic tuff. It is the eruptive character of the igneous rocks on which he specially dwells, showing by numerous sections the effects which the protrusion of the molten masses have had upon the surrounding rocks. He does not attempt to separate the intrusive from the interbedded sheets, nor to form a chronological arrangement of the whole.

Still more important was the sketch given by MACLAREN, in his classic "Geology of Fife and the Lothians,"‡‡ a work far in advance of its time. The

* Hutton's "Theory of the Earth," vol. i. p. 155, *et seq.*

† Playfair's "Illustrations of the Huttonian Theory," § 255, *et seq.*

‡ See "Trans. Roy. Soc. Edin." (1805), vol. v. p. 43.

§ See "Mem. Wern. Soc." ii. 178, 618 ; iii. 225 ; "Edin. Phil. Journ." i. 138, 352 ; xv. 386.

‖ "Trans. Roy. Soc. Edin." (1811), vi. p. 405.

¶ "Tracts and Observations in Natural History and Physiology," 8vo, Lond. 1799.

** "Trans. Roy. Soc. Edin." (1833), xiii. p. 39, 107.

†† "Mem. Wern. Soc." vii. p. 1. Published separately, 1838.

‡‡ Small 8vo, Edin. 1838, first partly published as articles in the *Scotsman* newspaper.

author clearly recognises that many of the igneous rocks were thrown out contemporaneously with the strata among which they occur. He constantly seeks for analogies among modern volcanic phenomena, and presents the igneous rocks of the Lothians not as so many petrographical varieties, but as monuments of different phases of volcanic action previous to the formation of the Coal-measures. His detailed descriptions refer chiefly to Arthur Seat and the Pentland Hills, to which alone the work was originally intended to refer. They may be cited as models of exact and luminous research. The portions referring to the rest of the basin of the Forth do not profess to be more than a mere sketch of the subject.

The first chronological grouping of all the intercalated sheets of igneous rock in the region was that made by myself for the Geological Survey. The general order of succession of the strata was carefully worked out, and the horizon of each sheet of volcanic rock could thus be definitely fixed. In the memoirs illustrative of Sheets 32, 33, and 34 the general structure of the country from Linlithgow to Berwick-on-Tweed was traced, and the part taken by the igneous rocks was there described.

Since the appearance of the maps and memoirs of the Survey, prolonged study of igneous rocks in other parts of Britain and abroad has given me further insight into the history of volcanic action in this district of Scotland. The application of microscopical examination has opened up a new field of inquiry, giving new methods of mineralogical analysis and comparison, and new aids in the investigation of ancient volcanic processes. I propose therefore, in the present memoir, to offer to the Society a general view of the volcanic phenomena associated with the Carboniferous rocks in the basin of the Forth, derived on the one hand from a study of the rocks in the field, and on the other from an examination and comparison of them under the microscope.

The subject thus divides itself naturally into two parts,—1st, The larger relations of the rocks to each other and to the associated stratified formations, including the geological structure of the masses, their chronology and the succession of events of which they are memorials; 2d, The minute and internal composition and relations of the rocks, chiefly as revealed by the microscope. The former subdivision may be termed Stratigraphical, the second Petrographical.

I. STRATIGRAPHY.

A. The Carboniferous Strata of the Basin of the Firth of Forth.

The Carboniferous system of Central Scotland consists of the following subdivisions :—

Coal-measures.	Upper red sandstones, nearly devoid of coal-seams. Coal-bearing sandstones, shales, &c. (upper or Flat coals).
Millstone Grit.	Thick white and reddish sandstones and grits.
Carboniferous Limestone Series.	Sandstones, shales, &c., with coal seams and three thin seams of encrinal limestone. Sandstones, shales, &c., with numerous seams of coal and ironstone (lower or Edge coals). Thick encrinal limestones, with some seams of coal.
Calciferous Sandstone Series.	White sandstones, oil-shales, some thin coals, and limestone (Burdie House). Red and grey sandstones and cornstones (Upper Old Red Sandstone) resting unconformably on Lower Old Red Sandstone.

At the outset it deserves to be kept in view that not only the basin of the Forth but the whole of central Scotland had already, long before the Carboniferous period, been the scene of some of the most stupendous volcanic eruptions which have been chronicled among the rocks of Great Britain. During the time of the Lower Old Red Sandstone the wide lake or inland sea which extended between the base of the Highland mountains and the Southern uplands was marked by two long lines of volcanic vents, from which prodigious volumes of lava and ashes were emitted. Even now, in spite of all denudation and dislocation, more than 5000 feet of volcanic material can be measured at the northern end of the Pentland Hills without reaching the top. In the Ochil Hills a depth of more than 6000 feet of similar rocks can be seen, and yet the bottom is not reached. Full details regarding these volcanic masses will be given in the second part of my Memoir on the Old Red Sandstone of Western Europe. In the meantime it is evident, that in tracing the history of the Carboniferous volcanoes, we must regard them as the diminished successors of an earlier series in the same region. That earlier series, however, seems to have been entirely closed long before the oldest of the Carboniferous eruptions. The two volcanic groups of rock are separated by a strong unconformability and extensive denudation, doubtless indicative of an interval of protracted duration.

In looking at the chronological distribution of the volcanic masses, we find that the true interbedded, as distinguished from the intrusive sheets, belong entirely to the two lower subdivisions of the Carboniferous system. They begin about the top of the red sandstone series which forms the base of the system, and continue at intervals till towards the top of the Carboniferous Limestone series, when they entirely cease. No truly interbedded lava or volcanic tuff has been found in either the Millstone Grit or the Coal-measures. Yet both these subdivisions have been invaded by extensive intrusive sheets. The date of the intrusion cannot be satisfactorily settled. It is evident, however, that between the volcanic action, represented respectively by the older and the later Carboniferous formations, an enormous interval must have elapsed. This question will be discussed in a subsequent part of the present paper.

The circumstances under which the older half of the Carboniferous system of central Scotland was accumulated require to be kept in mind when we attempt to follow the history of the contemporaneous volcanic phenomena of the region. At the beginning of the Carboniferous period, the conditions under which the Old Red Sandstone had been accumulated still in part continued. The great lacustrine basin in which the 20,000 feet of Lower Old Red Sandstone had been deposited had been in great measure effaced. But comparatively shallow areas of fresh or brackish water occupied its site. Its conglomerates and sandstones had been uplifted and fractured. Its vast ranges of volcanic material, after being deeply buried under sediment, had been once more laid bare, and now extended as ridges of land, separating the pools and lagoons which they supplied with sand and silt. We know little as yet of the flora which at the close of the long Old Red Sandstone period covered these ridges. It probably closely resembled that which, succeeding it, has been preserved in the sandstones and shales of the upper group of the Calciferous sandstones. Of the fishes, however, which frequented the waters, some knowledge has been gathered from the well-known sandstone of Dura Den. With many characteristic changes and differences, these fishes retain much of the peculiar type of the older divisions of the Old Red Sandstone. Though the strata in which they lie pass insensibly into and are intimately bound up with the overlying Carboniferous beds, the fossils themselves have an unmistakable Old Red Sandstone facies.

The red sandstones at the base of the Carboniferous system are almost everywhere unfossiliferous. Beyond Cockburnspath they have yielded a few scales of *Holoptychius* and other forms like those of Dura Den. Elsewhere their barren monotonous character contrasts them with the dark shales and white sandstones of the overlying group of rocks. That they were laid down on a very uneven floor is shown by the way in which they are overlapped by succeeding strata. Thus at the south end of the Pentland Hills they attain a thickness of upwards of 1000 feet, but only three miles towards the south they have entirely disappeared, and the Lower Old Red Sandstone is directly covered by the Carboniferous Limestone.

With the close of the epoch in which these red deposits were accumulated a great change took place in the geography of the Forth basin. Concentration of the water in the enclosed lagoons, and precipitation of iron-oxide amid the gathering sand and silt no longer prevailed. The sheets of water became more continuous, and were liable at intervals to irruptions of the sea. A more copious rainfall, at the same time, may perhaps be inferred from the thick zones of white sandstone, occasional bands of fine conglomerate, and abundant seams of shale. The constantly varying aspect of the strata must at least indicate much more varied climate and conditions of denudation and deposition than are presented to us by the monotonous barren red sandstones. The muddy floor of the shallow water must, in many places, have supported a luxuriant growth of vegetation, which is preserved in the occasional seams and streaks of coal. Numerous epiphytic ferns grew on the subærial stems and branches of the lycopodiaceous trees. Large coniferæ clothed the higher grounds, from which the streams brought down copious supplies of sediment, and whence a flood now and then transported huge prostrate trunks of pine.

It was during this condition of things, distinct from that which then prevailed in the rest of Scotland, that the Carboniferous volcanoes began their activity. The basin of the Firth of Forth was gradually dotted over with little volcanic cones, and here and there with long volcanic ridges formed by the confluence of lavas and showers of tuff. The whole area was all the while undergoing a process of slow subsidence. Cone after cone, more or less effaced by the waters which closed over it, was carried down and buried under the growing accumulation of sediment. But new vents of eruption opened elsewhere, throwing out for a time their dust or lava-streams, and then lapsing into quiescence as they slowly sank into the lagoon.

The occasional presence of the sea over some portions of the area is well shown by the occurrence of thin bands of limestone or shale, containing such fossils as *Orthoceras*, *Bellerophon*, and *Discina*. Yet the general estuarine or fresh-water character of the accumulations seems satisfactorily established, not only by the absence of undoubtedly marine forms from most of the strata, but by the abundance of ostracod crustacea (*Leperditia*), forming sometimes thick lenticular seams of limestone, such as might have been formed in distinct limited hollows, by the numerous scales, teeth, bones, and coprolites of small ganoids, and by the crowded remains of terrestrial vegetation, often admirably preserved among the shales.

There can be little doubt that the Calciferous Sandstone series of the Forth basin is a mingled estuarine and marine equivalent of the Lower Limestone shale, and even perhaps of the lower parts of the Carboniferous Limestone of England. The fossils in the marine bands just referred to make this point tolerably clear. But even the red sandstone group below can be shown from evidence, elsewhere obtainable in Scotland, to be coeval with a Carboniferous Limestone fauna outside the present Scottish area. The abundant fauna of the Carboniferous Limestone did not suddenly start into existence. It seems to have spread over the area of England before it had advanced into that of Scotland. It never, indeed, occupied the latter region so long, and so continuously, as it did the English and Irish tracts. Before it spread up towards the Highlands, it had been borne northward in excessive overflows of the sea, but did not succeed in establishing itself until the close of the Calciferous Sandstone series. At that time, a general subsidence of central Scotland appears to have taken place. A clear but shallow sea covered most of the ground between the chain of the Ochil and Lammermuir hills. At this epoch, the thick lower limestones were formed, which can now be traced continuously over so large an area. But that the sea did not obtain prolonged possession of the area is shown by the intercalation of sandstones, shales, and coal-seams among the limestones, and by the thick mass of similar strata under which the limestones were buried. The coal-seams, with their root-charged under-clays, point to the submergence of many successive terrestrial, or at least swampy surfaces, which had appeared over the site of the buried crinoid and coral limestones.

These changes of physical geography were accompanied in some places by abundant and continuous volcanic action. But the number of actual vents had decreased. Large tracts remained unvisited by any volcanic outbreak. Where the eruptions began most copiously they continued longest. Thus, in the south of Fife, they lingered on until the thick limestones and a considerable depth of the lower coals had been formed. But in Linlithgowshire, where they had been even more profusely poured out, they appeared intermittently, and on a gradually waning scale, until after all the lower coals had been laid down.

Before the Carboniferous Limestone series was finally concluded, volcanic action would appear to have ceased everywhere in the region of the Forth Basin. Not a trace of any interbedded volcanic rock has yet been met with in the Millstone Grit or in the Coal-measures. So far as appears, therefore, the outpouring of lava and ashes was entirely confined to the first half of the Carboniferous period. Nevertheless, the numerous intrusive masses of dolerite which traverse even the uppermost parts of the Coal-measures show that volcanic activity recommenced at some subsequent period. I shall be able in the present memoir to adduce new evidence regarding the nature of these much later eruptions. In the east of Fife they have been accompanied by large sheets of tuff which repose unconformably on the upper Coal-measures and the Carboniferous Limestone series, spreading over faulted and much denuded ground. They must thus either be post-Carboniferous, or at least must be separated from the highest remaining portion of the Carboniferous rocks by an enormous interval of time. Though I believe them to be post-Carboniferous, some probably of Permian, others possibly of Miocene date, I have judged it best to include them in the present communication. The Coal-measures, save where covered by these later volcanic sheets, have nothing overlying them but the drifts and other superficial accumulations.

B. Volcanic Districts.

Notwithstanding the limited extent of the Basin of the Firth of Forth, the sporadic character of its volcanic phenomena is singularly striking. Six districts can still be traced, each marked by its own independent eruptions, which differed from those of the neighbouring tracts not only in time, but even in petrographical character. These districts may be distinguished by the following topographical names:—1. Edinburgh; 2. East Lothian or Haddingtonshire; 3. West Lothian or Linlithgowshire; 4. Stirlingshire; 5. West Fife; 6. East Fife. (See Plate IX.)

1. *Edinburgh District.*—The interbedded volcanic masses of this district are confined to the near neighbourhood of Edinburgh, where they form the well-known eminences of Arthur Seat, Calton Hill, and Craiglockhart Hill. They consist both of lavas and tuffs, in beds varying from 10 to 50 feet or more in thickness. Their eruption began about the close of the red sandstone group, at the base of the Carboniferous system in Scotland, for their higher beds are intercalated with and covered by the lower portion of the white sandstone and dark shale group of the Calciferous Sandstones. This epoch was one of great volcanic activity over the southern half of Scotland. During its continuance there were erupted the lavas and tuffs of the Garlton Hills in Haddingtonshire, those which range along the southern flank of the Silurian uplands from near Dunse in Berwickshire, by Kelso, Rubers Law, Langholm, Birrenswark, and the Annan, to the mouth of the Nith at the foot of Criffel. To the same period of volcanic activity must be assigned the older parts of the great sheets of lava and tuff which extend through the north of Ayrshire, Renfrewshire, and Dumbartonshire, by the Kilpatrick and Campsie Fells to Stirling.

Throughout most of these volcanic tracts the lavas were chiefly the so-called "porphyrites," and the tuffs were dull-red or greenish rocks derived from the destruction of these lavas. In the Edinburgh district, the first lavas erupted were anamesites and basalts, and the tuffs were formed of their debris. In the latter half of the volcanic period the lavas became "porphyrites."

It is deserving of notice that the volcanic mass of Arthur Seat lies in the line of the older volcanic ridge of the Pentland Hills, and at a distance of scarcely two miles from the great vent of the Braid Hills. The long interval which separated these Lower Carboniferous volcanoes from those of the Lower Old Red Sandstone still left a weak part near the ancient vent. Through that line of weakness the volcano of Arthur Seat broke out. At a subsequent time, perhaps in the Permian period, another volcanic orifice was opened near, but not quite upon, the same site. From this last opening the upper and newer rocks of Arthur Seat were ejected.*

Owing to the fact that the line of junction between the red sandstones and the overlying upper group of the Calciferous Sandstones is almost everywhere obscured by faults, it is difficult to determine the number of distinct volcanoes in the Edinburgh district. Arthur Seat and Calton Hill no doubt form parts of the ejectamenta of the same vent. I formerly suggested that this vent may be represented by the neck of basalt forming the Castle Rock of Edinburgh. But there may have been another orifice further east, somewhere on the south side of Arthur Seat. I am now disposed to regard the tuff and anamesite of Craiglockhart Hill as the products of a separate vent which lay in the near neighbourhood of that locality, probably a little to the west.

Far to the south-west, on the borders of Lanarkshire, an isolated volcanic cone poured forth basaltic sheets and slight showers of tuff which now form a band, running for several miles, as a boundary between the two groups of the Calciferous Sandstones.

In Plate X. a series of vertical sections is given to show the nature and position of the interbedded volcanic sheets in the Lothians and Fife. From these sections it will be observed that in the Edinburgh district, where there is a maximum depth of about 500 feet of volcanic rocks, these lie near the base of the Carboniferous series. They occur at Arthur Seat, where the first eruption produced a stream of lava (Long Row), followed after an interval by greenish tuffs and volcanic breccias. Beautifully columnar as well as amorphous basalts overlie those fragmental strata, followed by sheets of dark dull-red "porphyrite," which form the remainder of the volcanic series. In the adjacent Calton Hill, the porphyrite beds are more split up with layers of tuff and breccia. (See fig. 24.)

Allusion must be made here to the intrusive sheets and veins which occur

* Descriptions of the geological structure of Arthur Seat will be found in Maclaren's "Geology of Fife and the Lothians," and in the "Geological Survey Memoir of Sheet 32, Scotland." Mr JUDD has offered an explanation of one part of the history of the hill (Quart. Journ. Geol. Soc., vol. xxxi. p. 131), which I believe to be quite untenable. It will be referred to elsewhere.

in the Edinburgh district. These rocks, though they did not reach the surface, must be regarded as subterranean portions of the volcanic series. Besides the sheets and veins at Arthur Seat, numerous smaller portions occur near Lochend, and underlying the city of Edinburgh. To the west an irregular belt of large sheets runs from the Water of Leith northwards into Fife.

2. *East Lothian District.*—This forms a very distinctly defined area of about 65 square miles. It includes the Garlton Hills, with a few outstanding eminences to the south of these heights, and most of the coast from near Dirleton to Dunbar. As shown in the fifth column (Plate X.), the volcanic masses, filling up most of the interval between the red sandstones and the base of the Carboniferous Limestone, must attain a thickness of possibly 1500 feet, though, owing to the paucity of sections, only an approximate estimate can be made. At the base of this thick pile of material lies a deep series of red and green tuff, resting upon red and white sandstones and red marls. These fragmental accumulations are admirably shown along the coast to the west of Dunbar, and on both sides of North Berwick. Abundantly interstratified in some parts of the tuff are seams of sandstone, blue and green shale, cement-stone and limestone. One thick band of limestone may be traced from near Tynningham House to Whittingham—a distance of about four miles; another patch appears near Rockville House; and a third at Rhodes, near North Berwick.

No fossils have been noticed in these limestones. The calcareous matter, together sometimes with silica, appears to have been supplied, at least in part, by springs, which may be looked upon as having formed part of the volcanic phenomena of the district. Parts of the limestone are vesicular, and contain a decayed zeolite, scattered crystals of pyrite, and cavities lined with dog-tooth spar. Some portions give out a strongly fœtid odour when freshly broken.

After the cessation of the showers of ash and bombs, lava began to flow, and continued to do so with apparently little intermission until the mass of the Garlton Hills had accumulated. No thick zones of tuff, nor inter-stratified layers of sedimentary rock, can anywhere be seen, separating the successive lava-beds, though it must be owned that the sections of the rocks are few and unsatisfactory. The earliest lavas were dark red, strongly augitic porphyrites. But the remaining, and much the larger portion, were dull-red, purple, pink, grey, brown, yellow, and even white fine-grained porphyrites, and "claystones."

One of the most interesting features in this district is the occurrence of numerous old volcanic orifices round the margin of the area. On the coast, both to the west and east of North Berwick, they may be seen in the form of necks of agglomerate, basalt, or porphyrite. North Berwick Law is a conspicuous example, and the Bass Rock is probably another. A beautiful instance occurs on the headland of St Baldred's Cradle (fig. 6), and several may be observed near Dunbar.* Again, on the south side of the volcanic sheets, a conspicuous neck rises in Traprain Law. As no necks appear among the hills to the south, nor among the red sandstone to the east, it is evident that the cones from which the volcanic mass of East Lothian was poured out formed a connected group in the shallow water at the northern base of the heights of Lammermuir. The lava and tuff occupy nearly the whole of the interval between the red sandstone group and the base of the Carboniferous Limestone series. Volcanic action was thus prolonged in East Lothian for a protracted period after it had died out in the Edinburgh district.

3. *West Lothian District.*—It is remarkable that while on the east side of Arthur Seat and the Pentland Hills not a single volcanic eruption, so far as we know, took place on the Mid-Lothian area during the whole of the Carboniferous period, the ground to the westward continued to be dotted with active vents throughout the deposition of the Calciferous Sandstones and Carboniferous Limestone series. The oldest eruptions of which any trace can be seen proceeded from small cones, chiefly of tuff. Towards the close of the Calciferous Sandstone period the volcanic activity increased. At the same time, the cones extended northwards into Fife. Some of them were of comparatively large size. The Binns Hill of Linlithgowshire, for example, which still forms a prominent elevation, rising to a height of 170 feet above its base, consists of a mass of fine green tuff, at least 350 feet thick, the vent being now filled up with a plug of basalt, which forms the summit of the hill. South-westwards from Binns the volcanic cones were grouped more closely together, and continued to throw out both showers of tuff and streams of basaltic lavas. These volcanic materials were interstratified with the ordinary sandstones, shales, and other strata of the Lower Carboniferous groups. The Burdie House limestone and Houston coal-seam may be traced among them. We can also detect some of the lower thick calcareous zones of the Carboniferous Limestone series, charged with corals, crinoids, and other characterstic fossils. But along one special tract the volcanic sheets so increased in bulk that at last a great bank of lava stretched continuously between Linlithgow and Bathgate, and prevented the deposition of a considerable portion of the coal-bearing section of the Limestone series, which is consequently not represented there, its place being taken by volcanic rocks. The general depression, however, that led to the formation of the thin upper limestones seems to have been accompanied here by a cessation of volcanic action. The latest interbedded lavas and tuffs lie almost immediately below the Calmy Limestone. Volcanic interstratifications die out there, and save in the form of intrusive masses to be immediately referred to, never reappear in any later formation in this district.

* See "Memoir on East Lothian," *Geol. Survey Memoirs*, chap. v.

The thickness of strata in a section through the most volcanic part of the heights south of Linlithgow is about 2200 feet. It will probably not be an over-estimate to place the proportion of lava and tuff in that section at 2000 feet.

Besides the necks and associated portions of igneous matter, the Linlithgow district presents numerous examples of intrusive igneous rocks belonging to an epoch long posterior to that of the Carboniferous volcanoes. They occur in two forms,—1st, As large sheets intruded into the Millstone Grit and Coal-measures; 2d, As dykes running in a general east and west direction through all the other rocks, aqueous and igneous, including even some of the large intrusive sheets. The dykes form a portion of that vast series which traverses Scotland and the north of England, and, as I have elsewhere shown, may with probability be referred to the Miocene period. They therefore do not belong to the subject of the present memoir. The intrusive sheets of later date than the Coal-measures are, as I have said, probably younger than any part of the Carboniferous system, if, indeed, some of them are not overflows from the Tertiary dykes. As they present, however, some interesting features bearing on the subterranean action of igneous matter, I shall include references to them in the sequel.

4. *Stirlingshire District.*—A relation may be traced between this district and that of Linlithgowshire, somewhat similar to what has already been stated to subsist between the Edinburgh and East Lothian volcanic areas. The Stirlingshire ground embraces a small part of the eastern prolongation of the Campsie Fells, which like the Garlton Hills consist chiefly of various "porphyrites" and tuffs of later date than the red sandstones at the base of the Carboniferous system. There can be little doubt that the two latter areas were contemporaneously the scene of the same conditions of volcanic activity. The distance between them is about forty-five miles. Yet, while from these two centres the same kind of volcanic rocks were being copiously ejected, in the intermediate volcanic district of West Lothian all the lavas were of basaltic types, while the tuffs presented the usual characters associated with these pyroxenic rocks. Not a single sheet or dyke of porphyrite has been met with in any part of that district, with the trifling exceptions at Calton Hill and Arthur Seat.

The volcanic history of the Stirlingshire district is sharply divided off into two periods. First comes the great pile of lava and tuff of the Campsie Fells. These immediately to the north of Kilsyth are seen lying conformably upon the upper part of the red sandstone group of the Calciferous Sandstone series. But except at the bottom they seem to be nearly without inter-stratifications of sandstones or other ordinary sedimentary strata. Their lower portions consist of slaggy porphyrite-lava and thick beds of fine-grained stratified tuff, with some bands of red, green, and grey clays, and cementstone, and a zone of white sandstone. The united depth of this igneous and aqueous series is at least 400 feet. It is succeeded above by about 600 feet of porphyrite in admirably well-defined beds or flows, which are separated as a rule, not by intercalations of tuff, but by the slaggy vesicular surfaces between the successive sheets.* Mr B. N. PEACH, in the course of the Geological Survey of this district, ascertained that while the volcanic masses attain a depth of about 1000 feet at Kilsyth, and swell out to far more than that thickness as they are followed westwards, they thin away rapidly eastward until about a mile north of Stirling, or 13 miles from Kilsyth, they disappear altogether, and the Calciferous Sandstone series closes up without any igneous intercalation. Nothing could show more strikingly the remarkably local character of the volcanic phenomena with which we are here concerned.

The second part of the volcanic history of the Stirlingshire district is represented by the numerous thick sheets of dolerite and other pyroxenic rocks which extend from the neighbourhood of Kilsyth, round the base of the Campsie Fells to beyond Stirling. These masses have been intruded among the Carboniferous Limestone series of strata, probably at a time before the consolidation and disturbance of these strata, seeing that they have been faulted and bent together with them.† They belong to an extensive belt of intruded matter which, keeping not far from the base of the Carboniferous Limestone series, extends to near the east end of the long county of Fife, and forms in its course the prominent eminences of the Cleish, Lomond, and Ceres Hills. We cannot be quite sure of the dates of these masses, some of them no doubt belong to the volcanic phenomena of the Carboniferous period, but some may be post-Carboniferous and even Tertiary.

5. *West of Fife District.*—For the sake of convenience, the volcanic rocks of the county of Fife (leaving out of account at present the intrusive sheets) may be grouped in two districts, separated from each other by the Dysart and Leven coal-fields, in which hardly any volcanic rocks occur. In the west of Fife we are presented with almost a counterpart of the features of West Lothian. From about the time of the Burdie House Limestone, until a considerable part of the upper or coal-bearing part of the Carboniferous Limestone series had been deposited, volcanic eruptions continued to take place there from small cones. One group of such orifices lay in that part of the district now occupied by the Saline and Cleish Hills. Conspicuous cones of fine green tuff remain there among the surrounding strata, to mark the sites of some of the vents. Another and more extensive group lay about six or eight miles eastward in the neighbourhood of Burntisland. In this interesting little area we meet with a series of tuffs and lavas occupying nearly the whole of the interval

* B. N. PEACH, in Explanation to Sheet 31, "Geo. Surv. Scotland," p. 15.

† B. N. PEACH, *op. cit.* p. 45.

between the Burdie House Limestone and the lower calcareous bands of the Carboniferous Limestone series. The interstratification of these volcanic materials with the estuarine beds, coal-seams, and marine limestone, can be admirably studied along the coast between Burntisland and Kinghorn. I hardly know any other section where the characters of true lava-streams are more strikingly displayed than in the two miles of shore between Pettycur and Seafield Tower. The hills around Burntisland likewise furnish similarly instructive examples of volcanic necks filled with agglomerate and basalt; also of intrusive sheets, and the effects of dislocation.

It will be observed that in the Saline and Burntisland tracts, volcanic action was contemporaneous with that in West Lothian, and ceased nearly about the same time, probably rather earlier. The thickest pile of volcanic rock in this district is that which lies between Burntisland and Kirkcaldy. It consists, like the bank south of Linlithgow, almost wholly of successive sheets of basaltic lavas, and must have a total thickness of upwards of 1500 feet. Yet, in spite of this considerable mass of igneous matter, its emission was confined within a limited area. The Burntisland lavas stretch southward, the island of Inchkeith being probably a part of the same group; but they did not reach the Edinburgh district, which as we have seen was wholly free from volcanic disturbance, except during the early period of the Arthur Seat eruptions.*

6. *East of Fife District.*—In some respects this is one of the most important volcanic areas in the basin of the Firth of Forth; for it contains an extraordinary number of volcanic vents, many of which have been admirably laid bare along the coast. It extends from the neighbourhood of Leven north-eastwards to St Andrews—a distance of 15 miles, with an average breadth of about 6 miles. In this tract, somewhere about fifty distinct orifices of eruption filled with tuff and agglomerate may be observed, besides many masses of dolerite and basalt, some of which may likewise mark the position of active vents. Many of the details to be given in a succeeding part of this paper regarding volcanic necks have been derived from a study of those in this interesting district.

Next to the number of the vents, the feature which most attracts notice in the east of Fife is the almost total absence of any interbedded volcanic rocks. The necks are hardly ever connected with any surrounding interstratified beds of tuff, such as are so abundant in the other districts. They rise indifferently through many various portions of the Carboniferous formations. In the eastern parishes they pierce some of the lower portions of the Calciferous Sandstone series; in the west they rise through the Coal-measures.

* A small outlier of tuff among the sandstones on the shore to the east of Cramond may be an exception to the statement in the text; but this mass might belong to some isolated cone between the West Lothian and Fife districts.

In the attempt to ascertain the geological horizon of these volcanic rocks, as we are deprived of the assistance which interbedded sheets afford, we must be content to be able to fix certain limits of time within which the eruptions must have occurred. From St Andrews to Elie a chain of vents may be traced, having the same general characters, and piercing alike the Calciferous Sandstones and the older part of the Carboniferous Limestone series. That these vents must in many cases be long posterior to the rocks among which they rise, is indicated by some curious and interesting kinds of evidence. They are often replete with angular fragments of shale, sandstone, and limestone, of precisely the same mineral characters as the surrounding strata, and containing the same organic remains in an identical state of fossilization. It is clear that the rocks must have had very much their present lithological aspect before the vents were opened through them. Again, the vents may often be observed to rise among much contorted strata, as for example along the crest of a sharp anticlinal arch, or across a synclinal basin. The Carboniferous rocks must thus have been considerably plicated before the time of the volcanic eruptions. In the next place, the vents often occur on lines of dislocation without being affected thereby. They must be posterior, however, not only to these dislocations, but also to much subsequent denudation, inasmuch as they overspread the rocks on each side of a fault without displacement. Hence we conclude with confidence, that the great period of volcanic activity in the East of Fife must have been posterior to most, if not all, of the Carboniferous period.

In the neighbourhood of Largo, further important evidence is presented, confirming and extending this conclusion. The highest member of the upper Coal-measures, consisting of various red sandstones, with red and purple clays, shales, thin coals, and ironstones, is prolonged from the Fife coal-field in a tongue, which extends eastward beyond the village of Lower Largo. It is well displayed on the shore, where every bed may be followed in succession along the beach for a space of nearly two miles. Two volcanic necks, presenting the same features as those which pierce the older portions of the Carboniferous system to the east, rise through these red rocks. We are thus carried not only beyond the time of the Carboniferous Limestone, but to the close of the very latest stage of the Carboniferous period in central Scotland. Connected with these and other vents farther north, there is a large area of tuff which has been thrown out upon the faulted and greatly denuded Carboniferous rocks. It may be traced passing from the red upper Coal-measures across the large fault which here separates that formation from the Carboniferous Limestone, and extending inland athwart different horizons of the latter series. Outlying fragmentary cakes of it may be seen resting on the upturned edges of the sandstones, shales, and coal-seams, even at a distance of some miles towards the north-west, proving that the fragmentary materials discharged from the vents spread over a considerable area. The subjoined section (fig 1), may serve as an illustration of the relation between this sheet of bedded tuff and the underlying rocks.

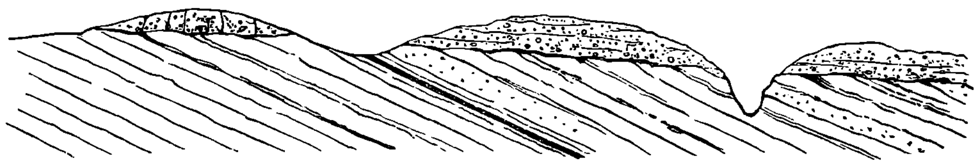

Fig. 1.—Section in brooks between Bonnytown and Baldastard, Largo.
a, Sandstone shales and coals of Carboniferous limestone series ; *b*, Unconformable tuff.

No proof could be more satisfactory that volcanic action was abundant in the east of Fife long after the formation of the latest member of the Scottish Carboniferous system. It is not impossible that some of the detached vents in other parts of the basin of the Firth of Forth may belong to as late a period. I have already suggested that this is probably the date of the later part of Arthur Seat. Some years ago I described a somewhat similar series of vents which pierce the Coal-measures of Ayrshire, and are connected with truly interbedded volcanic sheets in the overlying Permian sandstone series.* The Fife volcanoes may with much probability be referred to the same period.

Were there no other evidence to fix the epoch of volcanic activity in the east of Fife, it would be most logical to exclude the volcanic rocks of that district from the list of those belonging to the Carboniferous period. But to the north of Largo, and still more distinctly to the north-east of Leven, sections occur to show the contemporaneous outpouring of volcanic rocks in the Carboniferous Limestone period. The Leven section, seen in a ravine a little to the north-east of the town, is specially important. It presents a succession of red and green fine sandy tuffs, interstratified with fire-clays and sandstones, and containing a zone of basalt in the centre. These rocks lie not far from the top of the Carboniferous Limestone series. They prove that at least in one part of the district, volcanic action manifested itself long before the latest Carboniferous or Permian outbreak. It is quite possible, therefore, that some of these vents, the relations of which to the surrounding rocks are not such as to prove them to be of the latest date, may belong to some part of the time occupied by the deposition of the Carboniferous Limestone. I have not been able to discover any satisfactory means of discriminating them. I believe that if such older vents exist at all, they can form but a small minority among those which, on the grounds already stated, may be assigned to a much later period. But I have glady availed myself of this uncertainty, to include in this memoir an account of the east of Fife volcanic rocks, as they illustrate the phenomena of vents more fully than those of any other district in Scotland.

* "Geological Magazine," vol. iii. p. 243.

Taking the history of volcanic action as a whole within the basin of the Firth of Forth during the Carboniferous period, we can recognise two distinct types in the occurrence of the rocks,—1st, Successive streams of porphyrite lavas were poured out until their united mass attained a thickness of sometimes more than a thousand feet. Comparatively little tuff was ejected over these areas, except here and there, in the earlier stages of eruption. The lavas now form continuous sheets covering wide spaces of country, and rising into conspicuous ranges of hills. This is undoubtedly the prevalent type of the volcanic accumulations in the Carboniferous system in Scotland. The Campsie Fells in the Stirlingshire district, already described, are only the north-eastern extremity of the extensive volcanic plateaux of Dumbartonshire, Renfrewshire, and Ayrshire. The Garlton Hills, in the East Lothian, form a small detached area of the same character, and belonging to the same period; while only about 18 miles to the south-east, on the other side of the Lammermuir uplands, the great volcanic zone of Berwickshire begins with the same kind of rocks, and swells out towards the south-west into the ranges of Roxburgh and Dumfries. 2d, The other type is almost confined to the basin of the Firth of Forth. It consists in the protrusion of numerous detached masses of tuff, and of various augitic lavas never united into wide plateaux or extensive hill-ranges, but all pointing to local and sporadic action. The four districts in the Forth basin where this type is exhibited may, indeed, be viewed broadly as only one area lying between the two districts of the Campsie and Garlton Hills, which so characteristically exemplify the first type.

The local and independent character of the volcanic activity of the second type may be connected here with another feature, which cannot fail to strike the most casual observer. While the great hollow of central Scotland, between the Old Red Sandstone hills on the north, and the Silurian and the Old Red Sandstone heights on the south side, continued for fully a half of the Carboniferous period to be the scene of extraordinary volcanic activity, the eruptions, so far as we can judge, were always confined to the valley. It might be contended that possibly many sheets of tuff or of lava may have been stripped off the bounding hills on either side. But the fact remains, that even were it so, these volcanic materials were erupted from orifices in the valley, and not on the hills. In no case have I ever met with true volcanic necks on the hills on either side of the great central valley.* Denudation could not have removed

* In the valley of the Nith and its tributary the Carron Water, among the high grounds of Dumfriesshire, necks belonging to the Permian series of volcanoes occur. At the head of Lauderdale, Mr B. N. PEACH has observed a small neck coming through the Upper Old Red conglomerate, and possibly connected with the volcanic action in which the Berwickshire and Roxburghshire porphyrites were erupted. But in these cases the orifices have been opened in deep valleys among the hills. [Since this was written, Mr PEACH has met with a number of volcanic necks of Lower Carboniferous age in valleys of the Silurian uplands of Roxburghshire, extending to a distance of at least 10 miles from the edge of the lava-sheets.]

them; their absence makes it certain that the numerous volcanic vents were confined to the low grounds.

C. Structure of the Volcanic Masses.

The volcanic rocks associated with the Carboniferous formations in the Basin of the Firth of Forth may be conveniently grouped into four sub-divisions according to their mode of occurrence with reference to the surrounding strata. 1st, *Necks*, that is, masses of volcanic material occupying the space of former vents or orifices out of which the volcanic eruptions proceeded. 2d, *Intrusive Sheets, Dykes*, and *Veins*. These are portions of lava which never succeeded in forcing their way to the surface, but after penetrating some way upward, were arrested in their progress, and consolidated among the rocks. 3d, *Interbedded* or *Contemporaneous Lavas*, that is, masses of molten rock which were emitted at the surface, flowed out there in streams, and consolidated into sheets that lie conformably among the strata with which they are geologically contemporaneous. 4th, *Tuffs*, which occur in large stratified masses, or in small beds, either interstratified with ordinary sedimentary deposits, or accompanying sheets of lava.

1. *Volcanic Necks.*

General Characters.—A volcanic neck is a pipe or funnel which has been blown out of the earth's crust, and has been filled up with the solid materials ejected by the first or subsequent explosions. Viewed geologically, it may be regarded as a column of extraneous material usually in the main of volcanic origin, which descends from the surface to an unknown depth beneath. Unless disturbed by posterior subterranean movements, this column may be considered to be vertical, though any tilt subsequently affecting the rocks of the locality may have given it an inclination to one side. In the basin of the Firth of Forth there has been comparatively little displacement of this kind.

In their external aspect the necks form conspicuous features among the volcanic districts in which they occur. In the great majority of cases they rise as isolated cones or dome-shaped hills, circular or elliptical in outline, and for the most part with smooth grassy slopes. Where a dyke or boss of a hard rock, such as basalt, occurs in them, it usually stands out as a crag or knoll. Where the whole neck consists of an enduring rock of that kind, it forms a bolder, more abrupt eminence. Largo Law (fig. 2) may be taken as a singularly perfect example of the cone-shaped neck. Traprain Law and North Berwick Law illustrate the contour assumed when the rock is of a more enduring kind. One notable exception to the rule that necks form eminences at the surface, is furnished by the remarkable vent which occupies a wide

Fig. 2.—View of Largo Law from the east (the crag on the left, at the base of the cone, is a portion of a basalt-stream).

basin-shaped depression among the Campsie Fells. Yet, beyond its margin there occur some conspicuous examples of the usual prominent type, such as the Meikle Binn and Dungoil. Though not by any means the largest or most perfect of the vents in the basin of the Firth of Forth, the Binn of Burntisland presents in detail some of the most strikingly volcanic aspects of scenery anywhere to be seen in that region (fig. 14). Consisting of a dull green granular volcanic tuff, it rises abruptly out of the Lower Carboniferous formations to a height of 631 feet above the sea. Its southern slope has been so extensively denuded, that it presents steep craggy slopes and rugged precipices, which descend from the very summit of the cone to the plain below—a vertical distance of nearly 500 feet. Here and there the action of atmospheric waste has hollowed out huge crater-like chasms in the crumbling tuff. Standing in one of these it is not difficult to realise what must have been the aspect of the interior of these ancient Carboniferous volcanic cones, for the scene at once reminds one of the crater-walls of a modern or not long extinct volcano. The dull green tuff rises around in verdureless crumbling sheets of naked rock, roughened by the innumerable blocks of lava, which form so conspicuous an element in the composition of the mass. Ribs or veins of columnar basalt may be seen shooting up the declivities, and standing out prominently as black shattered walls. The frosts and rains of successive centuries have restored to the tuff its original loose gravelly character. It disintegrates rapidly, and rolls down the slopes in long grey lines of volcanic sand, precisely as it no doubt did at the time of its ejection, when it fell on the outer and inner declivities of the original cone.

The shape of the vents is on the whole circular or oval; but is subject to considerable irregularity. The admirable coast-sections in the east of Fife, between Largo and St Monans, as well as those of the shores of Haddingtonshire, expose many ground-plans of the vents, and permit these irregularities to be closely examined. The accompanying figure (fig. 3), exhibits some charac-

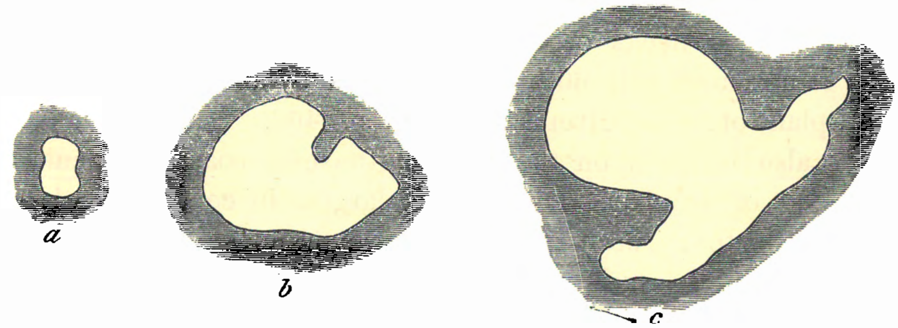

Fig. 3.—Ground plan of volcanic vents.

teristic forms of vents. Some of the eccentricities of outline no doubt arose from the irregular way in which the rocks through which an orifice was drilled yielded to the forces of explosion. This is often well shown by the veins and nests of tuff or agglomerate which have been forced into the rents or sinuosities of the orifices. In other cases, however, it is probable that what appears now as one volcanic neck, was the result of a shifting of the actual funnel of discharge, so that the neck really represents several closely adjacent vents. The necks at Kellie Law (fig. 4) show this arrangement very clearly. The Law itself (1) probably consists of two contiguous vents, while a third (2) forms a smaller cone immediately to the east. This slight lateral displacement of the vent has been noticed at many Tertiary and recent volcanic orifices. In the island or peninsula of Volcanello, for example, I observed three craters indicative of successive shiftings of the vent, the most perfect crater marking the latest and diminishing phase of the volcanic activity. The cones at Kellie Law may point to a similar series of events.

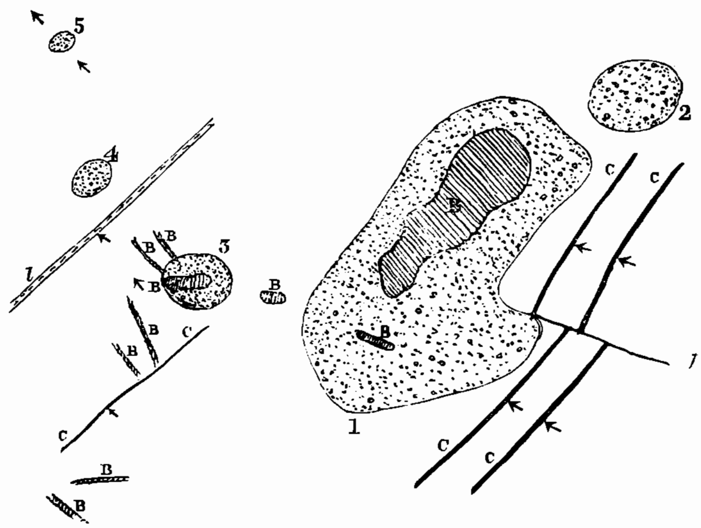

Fig 4.—Plan of volcanic necks at Kellie Law, east of Fife. 1, Kellie Law (tuff); 2, Carnbee Law (tuff); 3, 4, 5, small tuff necks; BB, basalt dykes and sheets; *cc*, coal-seams; *l*, limestone; *f*, fault. The arrows mark the dip of the strata through which the necks have been drilled.

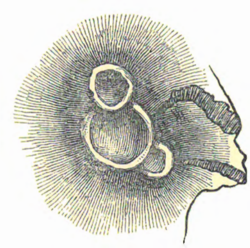

Fig. 5.—Plan of the craters in Volcanello, Lipari Islands.

The size of necks varies from only a few yards up to more than a mile in diameter. In the east of Fife, so remarkable for the number and perfect preservation of these features of volcanic action, one of the smallest and most completely exposed necks occurs on the shore at Newark Castle, near St Monans. It measures only 60 yards in length by about 37 yards in breadth. A ground-plan of it is given in fig. 11, p. 468. Some remarkably small necks may also be seen on the Haddingtonshire coast, particularly in the neighbourhood of Dunbar. One of the largest in central Scotland is that already referred to as occurring among the Campsie Hills between Fintry and Lennoxtown. It is upwards of a mile broad, and is surrounded by other minor necks, several of which form prominent hills.

Materials filling Necks.—These consist of (1) non-volcanic, and (2) volcanic rocks.

1. In some minor necks the vent has been entirely or in great part filled with angular debris of the ordinary rocks of the neighbourhood. In the western neck on the Largo shore, for example, which rises through the red rocks of the upper Coal-measures, the material consists largely of fragments of red sandstone, clay, and shale. Some small necks, exposed in the ironstone workings near Carluke, were found to be filled with debris of black shale and ironstone. At Burntisland fragments of the well-marked cyprid limestone and shale abound. Between Elie and St Monans the tuffs are sometimes almost wholly composed of debris of black shale and encrinal limestone. At Niddry, in Linlithgowshire, large blocks, several yards in length, and consisting of different layers of shale and cement-stone, may be seen imbedded at all angles in the tuff.

Where in these minor vents we encounter only the debris of non-volcanic rocks, we may infer that the volcanic action was limited to the explosion of steam whereby the rocks were dislocated, and an orifice communicating with the surface was drilled through them. No true volcanic rock in these cases appeared, but the pipes were filled up to perhaps not far from the surface by the falling back of the shattered debris. A little greater intensity or farther prolongation of the volcanic action would bring the column of lava up the funnel, and allow its upper part to be blown out as dust and lapilli; while still more vigorous activity would be marked by the rise of the lava into rents of the cone or its actual outflow at the surface. Every gradation in this scale of progress may be detected among the Carboniferous volcanoes of this region.

But though large cones might be built up by the long-continued emission of volcanic products, the first stage in these, as in the minor vents, must always have consisted in the perforation of the solid crust by explosion, and the consequent production of debris from the disrupted rocks. We may therefore expect that underneath the pile of thoroughly volcanic ejections traces of the first explosion must exist. I have been much struck with the fact that in the east of Fife such traces may frequently be found here and there on the outside of the vents. At Largo, and again between Elie and St Monans, I have observed that in the ground-plan exposed upon the shore the mass of material adhering to the wall of a neck often consists largely or even wholly of debris of sandstone, shale, and limestone, while the central and chief mass is made up of green tuff or agglomerate, with occasional pieces of the surrounding stratified rocks scattered through it. It seems probable, therefore, that the sections of these Fife necks, now exposed by the present beach, do not lie far below the original crater-bottoms.

Some light might be expected to be thrown upon the phenomena in an active volcanic chimney by the condition of the fragments of recognisable sedimentary rocks imbedded in the ejected debris which has filled up the orifice. But the assistance from this source is neither so full nor so reliable as could be wished. In a great many cases indeed the fragments of shale, sandstone, and other sedimentary strata are so unchanged that they cannot on a fresh fracture be distinguished from the parent beds at a short distance from the vent. The *spirifers, lingulæ,* crinoids, cyprid-cases, ganoid scales, and other fossils, are often as fresh and perfect in the fragments of rock imbedded in tuff as they are in the rock *in situ*. In some cases, however, distinct, and occasionally even extreme, metamorphism may be detected, varying in intensity from mere induration to the production of a crystalline texture. The amount of alteration has depended not merely upon the heat of the volcanic vent, but also in great measure upon the susceptibility of the fragments to undergo change.

My friend Dr HEDDLE endeavoured to estimate the temperature to which fragments of shale, &c., in tuff-necks of the Fife coast had been subjected. He found that the bituminous shales had lost all their illuminants, and of organic matter had retained only some black carbonaceous particles; that the encrinal limestones had become granular and crystalline; that the sandstones presented themselves as quartzite, and that black carbonaceous clays showed every stage of a passage into Lydian-stone. He inferred from the slight depth to which the alteration had penetrated the larger calcareous fragments, that the heat to which they had been exposed must have been but of short continuance. As the result of his experiments, he concluded that the temperature at which the fragments were finally ejected from the volcanic vents probably lay between 660° and 900° Fahr.*

It may be perhaps legitimate to infer that while the fragments which fell back into the volcanic funnel, or which were detached from the sides of the vent, after having been exposed for some time to intense heat under considerable pressure, would suffer more or less metamorphism, those on the other

* "Trans. Roy. Soc. Edin." xxviii. p. 487.

hand, which were discharged by the æriform explosions from the cool upper crust, on the first outburst of a vent, would not exhibit any trace of such a change. Where, therefore, we meet with a neck full of fragments of unaltered stratified rocks, we may suppose it to have been that of a short-lived volcano where, on the other hand, the fragments are few and much altered, we may infer that they mark the site of a vent which continued longer active.

2. The volcanic rocks of the necks consist occasionally of (*a*) some form of lava, but more usually of (*b*) fragmentary materials, with or without veins and pipes of lava.

(*a*) In various parts of the Basin of the Firth of Forth occur circular or oval bosses of basalt, dolerite, or porphyrite, which exactly resemble in contour the typical necks of tuff, and occur among interstratified rocks in such a manner as to suggest that they mark the sites of volcanic vents. Traprain Law and North Berwick Law are conspicuous examples. Each of these eminences rises in the midst of tuffs and lavas, and may not improbably be a portion of the lava column which rose in a volcanic pipe. A smaller but very perfect example

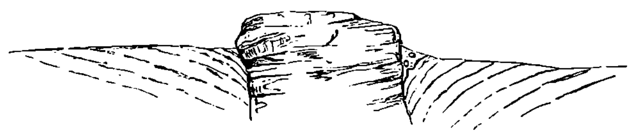

Fig. 6.—Section of Porphyrite neck, in sandstones, Shore of Haddingtonshire.

(fig. 6) occurs on the shore to the east of North Berwick Law.* The Castle rock of Edinburgh may be another. In these cases we probably see a deeper part of the pipe than that in which fragmentary materials accumulated.

(*b*) In the great majority of cases the necks are filled with fragmentary volcanic detritus. Sometimes this material consists of a coarse utterly unstratified mass or agglomerate of different lava blocks, angular and subangular, varying in size up to a diameter of a yard or more. The later agglomerate of Arthur Seat may be taken as an illustration of the coarsest variety. In other cases it is a breccia of small angular and subangular lava fragments. Most frequently it is a more or less compact or gravelly tuff, composed of a fine comminuted paste of volcanic dust and sand, full of rounded and subangular blocks and bombs of basalt, porphyrite, or other form of lava. In the east of Fife some of the necks contain a remarkable compact volcanic sandstone, composed of the usual detritus, but weathering into spheroidal crusts so as externally to be readily mistaken for some form of basalt rock. There can be little doubt that this variety of rock was originally a volcanic mud. The lithological details of the tuffs, however, will be given in a later part of this memoir.

* See "Geology of East Lothian," *Geological Survey Memoir*, p. 40.

It is to be observed that the tuff in the necks of each district partakes of the nature of the lava emitted in that district. In the East Lothian and Stirlingshire areas, for example, where the lavas were the so-called porphyrites, the tuff consists of the debris of these rocks. Elsewhere among basaltic lavas, the tuffs have a characteristic dirty green colour, and in this as well as in other respects show that they have been derived from these rocks. The ejected fragments contained in the tuffs bear the same relation to the surrounding lavas. In those cases where, as in so many of the vents of the east of Fife, no lava flowed out at the surface, we can yet tell from the character of the abundant ejected fragments what was the nature of the molten rock which ascended the volcanic chimney, and produced by its ebullition the abundant showers of tuff.

The lava blocks in the tuffs and agglomerates are usually rounded or sub-angular. Pear-shaped blocks or flattened discs or hollow spherical balls are hardly ever to be observed, though I have noticed a few examples in the tuffs of Dunbar and Elie. A frequent character of the blocks is that of roughly rounded, highly amygdaloidal pieces of lava, the cellular structure being specially developed in the interior, and the cells on the outside being often much drawn out round the circumference of the mass. Blocks of this kind, two or three feet in diameter, may be seen at some of the Elie vents. They were probably torn from the cavernous, partially consolidated, or at least rather viscous, top of a lava column. Most of the stones, however, suggest that they were produced by the explosion of already crusted lava, and were somewhat rounded by attrition in their ascent and descent. The vents filled with such materials must have been the scene of prolonged and intermittent activity; successive paroxysms resulting in the clearing out of the hardened lava column in the throat of the volcano, and in the rise of fresh lava, with abundant ejection of dust and lapilli. Corroborative evidence that the intervals of explosion were separated by long periods of quiescence is furnished by the fragments of wood to be afterwards referred to, and likewise by the numerous pieces of stratified tuff frequently to be noticed imbedded with the other debris in a neck. These angular blocks of older tuff resemble in general petrographical character parts of the tuff among which they are imbedded. There can be little doubt that they are portions of the volcanic debris which solidified inside the crater, and which was blown out in fragments by subsequent explosions. In a modern volcano a considerable amount of stratified tuff may be formed inside the crater. The ashes and stones thrown out during a period of activity fall not only on the outer slopes of the cone, but on the steep inner declivities of the crater, where they arrange themselves in beds which dip at high angles towards the crater bottom. This feature is well seen in some of the extinct cones in the Neapolitan district. At Astroni, for example, great sheets of well-bedded trachytic tuff lie on the inner slopes of the crater. (See fig. 9.)

One of the most curious and puzzling features in the contents of the tuff necks is the occurrence there of crystals and fragments of minerals, often of considerable size, which do not bear evidence of having been formed *in situ*, but rather of having been ejected with the other detritus. Dr HEDDLE has noticed this fact, and has described some of the minerals which occur in this way. The following list comprises the species which he and I have noticed chiefly in the vents of the East of Fife:—

Hornblende, in rounded fragments of a glassy black cleavable variety.

Augite, sometimes in small crystals, elsewhere in rounded fragments of an augitic glass.

Orthoclase (Sanidine), abundant in worn twin crystals in the tuffs of the East of Fife.

Biotite.

Pyrope, in the tuffs (and more rarely in the basalts) of Elie.

Nigrine, common in some of the dykes, more rarely in the tuffs of Elie.

Saponite, Delessite, and other decomposition products.

Semi-opal, one specimen found in later tuff of Arthur Seat.

Asphalt, abundant at Kincraig, near Elie.

Fragments of wood, with structure well preserved, may be included here.

In his paper on the Felspars, Dr HEDDLE has described from the neck of tuff at Kinkell, near St Andrews, large twin crystals of a glassy orthoclase, which are invariably much worn, and preserve only rudely the form of crystals. He justly remarks that they have no connection with drusy cavity, exfiltration vein, or with any other mineral, and look as if a portion of their substance had been dissolved away. Internally, however, they are quite fresh and brilliant in lustre, though sometimes much fissured.*

The tuffs at Elie are full of similar crystals. I obtained from one of the necks east of that village, a specimen which measures 4 inches in length, 3½ in breadth, and 2¼ in thickness, and weighs about 2 lbs. It is, however, a well-striated felspar. From the same tuff I procured an orthoclase twin in the Carlsbad form. All the felspar pieces, though fresh and brilliant internally, have the same rounded and abraded external appearance.

The fragments of hornblende form a characteristic feature in several of the Elie dykes (to be afterwards described), and in the neighbourhood of these intrusive rocks occur more sparingly in the tuff. It is a glossy-black cleavable mineral, in rounded pieces of all sizes, up to that of a small egg. Dr HEDDLE obtained a cleavage angle of 124° 19′, and found on analysis that the mineral was hornblende.†

Augite occurs sparingly in two forms among the necks. Some years ago, I

* Trans. Roy. Soc. Edin. vol. xxviii. p. 223.

† *Op. cit.* xxviii. 522.

obtained small crystals from the red upper tuff of Arthur Seat, recalling in their general appearance those of Somma. Lumps of an augitic glass have been found by Dr HEDDLE, sometimes as large as a pigeon's egg, in two of the dykes at Elie, and in the tuff at the Kinkell neck, near St Andrews. He observed the same substance at the Giant's Causeway, both in the basalt, and scattered through one of the interstratified beds of red bole. I recently found much larger rounded masses of a similar augitic glass, but with a distinct trace of cleavage, in a volcanic vent of Upper Old Red Sandstone age, at John o' Groat's House.*

Biotite is not a rare mineral in some of the tuffs. It may be obtained in the stratified tuffs of Dunbar, in plates nearly an inch broad; but the largest specimen I have obtained is one from the same Elie vent which yielded the large felspar fragment. It measures $2\frac{1}{2} \times 2 \times \frac{1}{2}$ inches. These mica tables, like the other minerals, are abraded specimens.

That these various minerals were ejected as fragments, and have not been formed *in situ*, is the conclusion forced upon the observer who examines carefully their mode of occurrence. Some of them were carried up to the surface by liquid volcanic mud, and appear in dykes like plums in a cake. But even there they present the same evidence of attrition. They assuredly have not been formed in the dykes any more than in the surrounding tuff. In both cases they are extraneous objects which have been accidently involved in the volcanic rocks. Dr HEDDLE remarks that the occurrence of the worn pieces of orthoclase in the tuff is an enigma to him. I have been as unable to frame any satisfactory explanation of it.

Arrangement of Materials in Necks of Tuff and Agglomerate.—It might have been thought that in the throat of a volcano, if in any circumstances, loose materials should have taken an utterly indefinite amorphous aggregation. And this is usually the case where these materials are coarse and the vent small. Oblong blocks are found stuck on end, while small and large are all mixed confusedly together. But in the numerous cases where the tuff is more gravelly in texture traces of stratification may usually be observed. Layers of coarse and fine material succeed each other, as they are seen to do among the ordinary interstratified tuffs. The stratification is usually at high angles of inclination, often vertical. So distinctly do the lines of deposit appear amid the confused and jumbled masses, that an observer may be tempted to explain the problem by supposing the tuff to belong, not to a neck, but to an interbedded deposit which has somehow been broken up by dislocations. That the stratification, however, belongs to the original volcanic vents themselves, is made exceedingly clear by some of the coast-sections in the East of Fife. On both sides of Elie examples occur in which a distinct circular disposition of the bedding can be traced corresponding to the general form of the neck. The accompanying

* *Op. cit.* xxviii. p. 481, *et seq.*

ground plan represents this structure as seen in the neck which forms the headland at the harbour. Alternations of coarse and fine tuff with bands of coarse agglomerate, dipping at angles of 60° and upwards, may be traced round about half of the circle. The incomplete part may have been destroyed by the formation of another contiguous neck immediately to the east. To the west of Earlsferry another large, but also imperfect, circle may be traced in one of the shore necks. A quarter of a mile further west rises the great cliff-line of Kincraig, where a large neck has been cut open into a range of precipices 200 feet high, as well as by a tide-washed platform more than half a mile long. The inward dip and high angles of the tuff are admirably laid bare along that portion of the coast line. The section in which almost every bed can be seen, and where, therefore, there is no need for hypothetical restoration, is as shown in fig. 8.

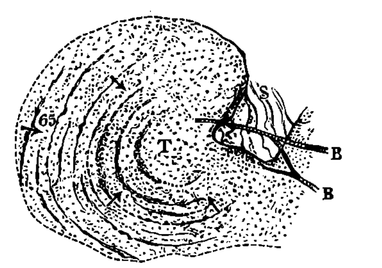

Fig. 7.—Ground-plan of Volcanic Neck, Elie Harbour, showing circular deposition of the stratification.

T, Tuff of the neck, the arrows showing its inward dip, BB, Dykes, S. Sandstones and shales, through which the neck has been opened.

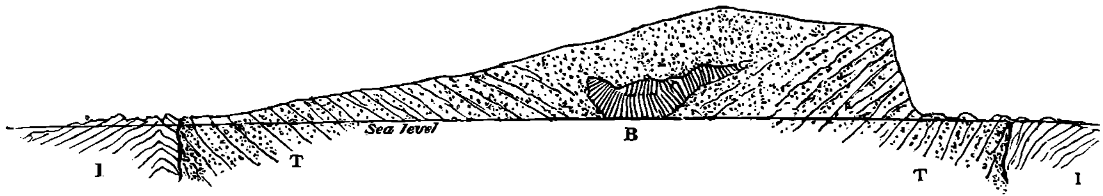

Fig. 8.—Section across the great vent of Kincraig, Elie, on a true scale, vertical and horizontal, of six inches to a mile.

1, Sandstones, shale, &c., of Lower Carboniferous age, plunging down toward the neck T ; B, columnar basalt.

I have already referred to the frequently abundant pieces of stratified tuff, found as ejected blocks in vents filled with tuff, and to the derivation of these blocks from tuff originally deposited within the crater. There can, I think, be little hesitation in regarding the stratification of these Fife vents as exhibitions of this same operation. The general dip inwards from the outer rim of the vent strikingly recalls that of some modern volcanoes. By way of illustration, I give here a section of part of the outer rim of the crater of the Island of Volcano, sketched by myself in ascending the mountain from the north side (fig. 9). The crater wall at this point consists of two distinct parts,—an older tuff (*a*), which may have been in great measure cleared out of the crater before the ejection of this newer tuff (*b*). The latter lies on the outer slope of the cone at the usual angle of 30°. It folds over the crest

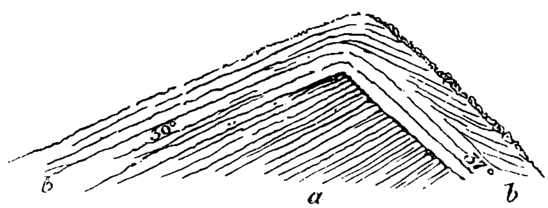

Fig. 9.—Section of part of crater rim, Island of Volcano.

of the rim, and dips down to the flat tuff-covered crater bottom, at an angle of 37°. These are its natural angles of repose.

Applying modern analogies of this kind, I have been led to conclude that the stratification so conspicuous in the tuff of the Carboniferous vents throughout central Scotland belongs to the interior of the crater and the upper part of the volcanic funnel. These stratified tuffs, on this view of their origin, must be regarded as remains of the beds of dust and stones which gathered within the crater and volcanic orifice, and which, on the cessation of volcanic action, sometimes remained in their original position, or were dislocated, and slipped down into the cavity beneath. That the tuffs consolidated on slopes, perhaps quite as steep as those of Volcano, is now and then indicated by an interesting structure. The larger stones imbedded in the layers of tuff may be observed to have on their fronts in one direction a small heap of coarse gravelly debris, while fine tuff is heaped up against their opposite side. This arrangement doubtless points to deposit on a slope of loose debris, from which the larger blocks protruded so as to arrest the smaller stones, and allow the fine dust to gather behind.

The frequent evidence of great disturbance in the bedding of the tuff within the vents may be connected with some kind of collapse, subsidence, or shrinkage of the materials in the funnel below. That a movement of this nature did take place is shown by the remarkable bending down of the strata round the margins of the vents, as will be described in the sequel.

Dykes, Pipes, and Cakes of Lava in Necks of Tuff and Agglomerate.—The minor vents for the most part contain only fragmentary materials; but those of larger size usually present masses of lava in some characteristic forms. In not a few cases the lava has risen in the central pipe and hardened there into a column of solid rock. Subsequent denudation, by removing most of the cone, has left the top of this broad column projecting as a round knoll upon the hill top. Arthur Seat presents a good example of this structure. Where the denudation has not proceeded so far, we may still meet with a remnant of the cake of lava which sometimes overflowed the bottom of a crater. The summit of Largo Law affords indications of this arrangement. That cone of tuff is capped with basalt, evidently the product of successive streams, which welling out irregularly covered the crater bottom with hummocks and hollows. The knolls are beautifully columnar, and sometimes show a divergent arrangement of the prisms.

But the most frequent form assumed by the lava in the necks is that of veins or dykes running as wall-like bands through the tuff or agglomerate. Many admirable examples might be cited; the most striking and accessible being those of the Fife coast. The shores between Largo and St Monans abound with them. These intruded masses vary in breadth from mere threadlike veins up to dykes several yards in breadth, which sometimes expand into large irregular lumps. They generally consist of some form of basalt (including all the fine varieties of dolerite); now and then, as at Ruddon Point, near Elie, they are amygdaloidal; and it may be observed among them, as among dykes in general, that where the amygdaloidal texture is developed, it is apt to occur most markedly in the central part of the vein, the amygdules running there in one or more lines parallel with the general trend of the mass.

That the basalt of these veins and dykes was sometimes injected in an extremely liquid condition is shown by its frequently exceedingly close homogeneous texture. Within the neck on the shore to the west of Largo, the basalt assumes in places an almost flinty texture, which here and there passes into a thin external varnish of tachylite. A farther indication of the liquidity of the original rock seems to be furnished by the great number of included extraneous fragments here and there to be observed in the basalt.

But besides basalt other materials may more rarely be detected assuming the form of dykes or veins within the necks. Thus, at the Largo neck just referred to, strings of an exceedingly horny quartz-felsite accompany the basalt,—a remarkable conjunction of acid and basic rock within the same volcanic chimney. To the east of Elie some dykes which stand out prominently on the beach consist of an extremely compact volcanic mudstone stuck full of worn twin crystals of orthoclase and pieces of hornblende and biotite. So like is this rock to one of the decomposing basalts, that its true fragmental nature may easily escape notice, and it might be classed confidently as a somewhat decayed basalt. A considerable amount of a similar fine compact mudstone is to be seen round the edges of some of the Elie vents.

A columnar arrangement may often be observed among the basalt dykes. When the vein or dyke is vertical the columns of course seem piled in horizontal layers one above the other. The exposed side of the dyke then reveals a wall of rock, seemingly built up of hexagonal or polygonal, neatly fitting blocks of masonry, as may be seen on the Binn of Burntisland. An inclination of the dyke from the vertical throws up the columns to a proportional departure from the horizontal. Sometimes a beautiful fan-shaped grouping of the prisms has taken place. Of this structure the Rock and Spindle, near St Andrews, presents a familiar example. Much more striking, however, though much less known, is the magnificent basalt mass of Kincraig, to the west of Elie, where the columns sweep from summit to base of the cliff, a height of fully 150 feet, like the Orgues d'Expailly, near Le Puy in Auvergne (fig. 10).

The veins or dykes seldom run far, and usually present a more or less tortuous course. No better example of these characters can be cited than that of the veins on the south front of the Binn of Burntisland (fig. 14). These vary in breadth from 5 or 6 feet to scarcely so many inches. They bifurcate, and rapidly disappear in the tuff, one of them ascending tortuously to near the top of the cliff. They at once recall the appearance of the well-known dykes in the great crater wall of Somma.

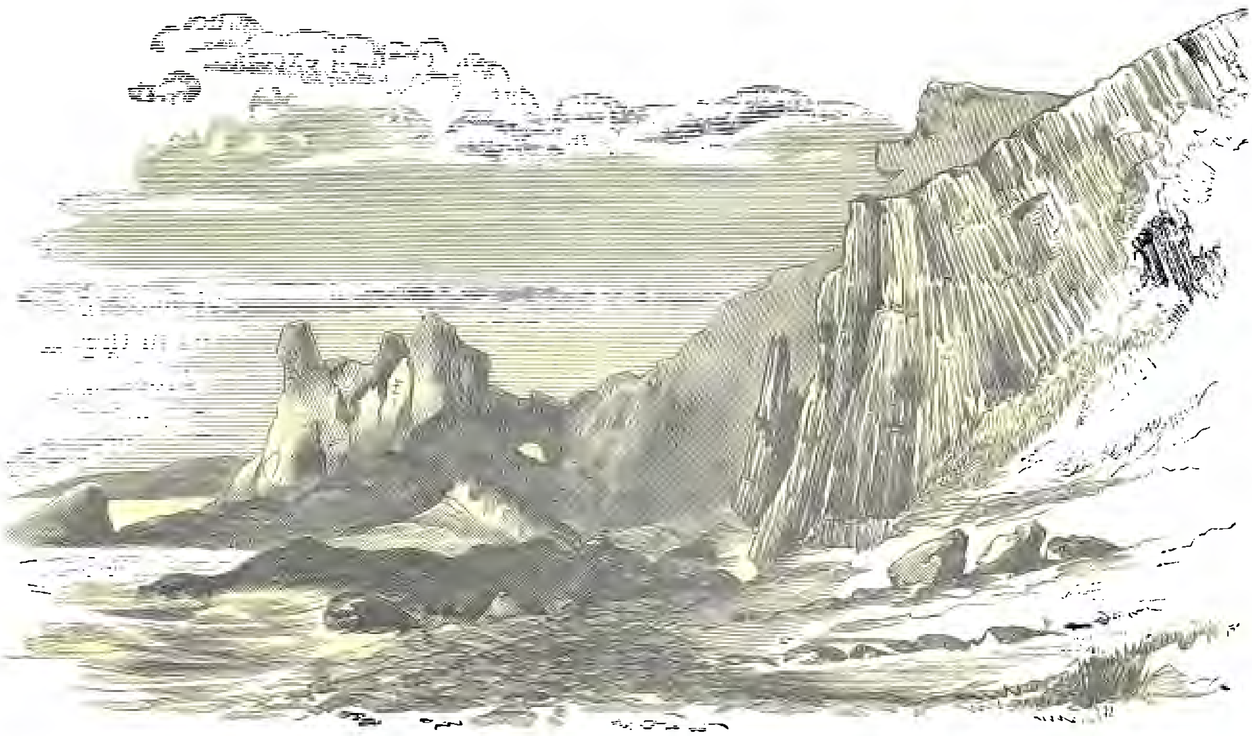

Fig. 10.—Columnar basalt in vent at Kincraig, Fife.

That many of these dykes served as lines of escape for the basalt to the outer slopes of the cone is highly probable, though denudation has usually destroyed the proofs of such an outflow. In some of the Fife necks a distinct radiation of the dykes from the centre of the neck is still traceable. This structure is most marked on the south cone of Largo Law, where a number of hard ribs of basalt project from the slopes of the hill. Their general trend is such that if prolonged they would meet somewhere in the centre of the cone. On the south-east side of the hill a minor eminence, termed the Craig Rock, stands out prominently. It is oblong in shape, and like the dykes, points towards the centre of the cone. It consists of a compact columnar basalt, the columns converging from the sides towards the top of the ridge. It looks like the fragment of a lava-current which flowed down a gully on the outer slope of the cone. (B′ in fig. 13.)

The veins of basalt are not confined to the necks, but may be seen running across the surrounding rocks. The shore at St Monans furnishes some instructive examples of this character. As the veins thin away from the main mass of basalt, they become more close-grained and lighter in colour; and when they enter dark shales or other carbonaceous rocks, they pass into that peculiar white earthy clay-like variety known as "white-rock" or "white-trap."

Junction of the Necks with the surrounding Rocks.—In a modern volcano no opportunity is afforded of examining the effects which have been produced upon the rocks through which the volcanic vent has been opened, except now and then among the detached fragments ejected. But in the Basin of the Firth of Forth a numerous series of coast sections lays bare this relation in the most satisfactory manner. The superincumbent cones have been swept away, and we can examine, as it were, the very roots of the old volcanoes. The margin of a neck or volcanic vent is thus found to be almost always sharply defined. The rocks through which the vent has been drilled have often been cut across, as if a huge auger had been sunk through them. This is well displayed in the beautifully perfect neck already cited at Newark Castle, near St Monans (fig. 11). The strata through which this neck rises consist of shales, sandstones, thin coal, and encrinal limestones, dipping in a westerly direction at angles ranging from 25° to 60°. At the south end of the neck they are as sharply truncated as if by a fault. Elsewhere they are much jumbled, slender vein-like portions of the tuff being insinuated among the projecting portions. A large vertical bed of sandstone, 24 yards long by 7 yards broad, stands up as a sinuous reef on the east side of the vent (*s*, fig. 11). It is a portion of some of the surrounding strata, but is entirely surrounded with agglomerate, so far as can be seen at the surface. Here and there the shales have been excessively crumpled, and at the north end have been invaded by a vein of basalt which, where it runs through them, assumes the usual clay-like character. As shown in the drawing (fig. 11), the strata have been blown out, and their place has been occupied by a corresponding mass of volcanic agglomerate. They have undergone comparatively little alteration. In some places they have been hardened, but their usual texture and structure remain unaffected.

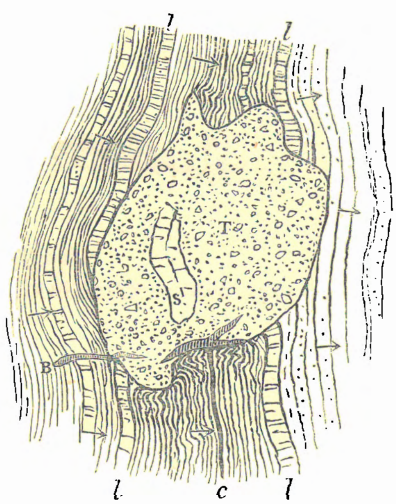

Fig. 11.—Plan of volcanic neck of agglomerate on beach near St Monans.

T, Neck of tuff enclosing a mass of sandstone (*s*), and piercing sandstones and shales with beds of limestone (*l*, *l*,), and a thin seam of coal (*c*); B, basalt "white trap" dyke. The arrows show the dip of the strata.

In other instances the boundary-line between the neck and the surrounding rocks is less sharply marked. Not infrequently the latter, as laid bare on beach-sections, protrude in tongues and irregular projections into the neck, while the tuff or agglomerate runs in veins and dykes, or fills up indentations in the boundary walls. This structure is illustrated by fig. 12, which represents a

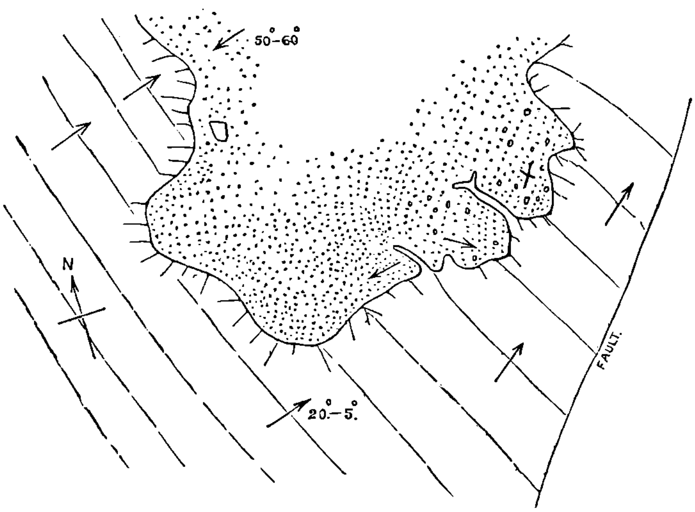

Fig. 12.—Ground-plan of Tuff-neck, shore east of Dunbar.
(The surrounding rocks are sandstones, which are much hardened round the vent in the zone marked by the short diverged lines. See "Geology of East Lothian," *Mem. Geol. Survey.*)

ground-plan of a neck in the East Lothian district. In some cases, as already stated, particularly in the east of Fife, injections of a kind of volcanic mudstone have filled up rents in the surrounding rocks, so as to look like true lava dykes or veins.

In the great majority of the shore-sections, a remarkable change of dip is observable among the strata round the edge of each vent. No matter what may be the normal dip of the locality, the beds are bent sharply down towards the wall of the neck, and are frequently placed on end. The structure (shown in figs. 6 and 8) is precisely the reverse of what might have been anticipated, and can hardly be due to the upward volcanic explosions. It is usually associated with considerable metamorphism in the disturbed strata. Shales are converted into porcellanite or various jaspery rocks, according to their composition. Sandstones pass into a distinct quartz-rock, with its characteristic lustrous fracture. It is common to find the vents surrounded by a ring of this altered sandstone, which from its hardness and vertical or highly inclined bedding, stands up prominently on the beach (as in fig. 12), and serves to mark the position of the necks from a distance.

I have not been able to find an altogether satisfactory explanation of the inward dip of the strata round the vents. Taking it in connection with the metamorphism, I am inclined to believe that it took place after the long-continued volcanic action which had hardened the rocks round the volcanic pipe had ceased, and as the result of some kind of subsidence within the vent.

The outpouring of so much tuff and lava as escaped from many of the volcanoes would doubtless often give rise to cavities underneath them, and on the decay of volcanic energy there might be a tendency in the solid or cavernous column filling up the funnel, to settle down by mere gravitation. So firmly, however, did much of it cohere to the sides of the pipe, that if it sank at all, it could hardly fail to drag down a portion of these sides. So general is this evidence of downward movement in all the volcanic districts of Scotland where the necks have been adequately exposed, that the structure may be suspected to be normal to all old volcanic vents. It has been observed among the shore-sections of the volcanoes of the Auckland district, New Zealand. Mr C. HEAPHY, in an interesting paper upon that district, gives a drawing of a crater and lava-stream abutting on the edge of a cliff where the strata bend down towards the point of eruption, as in the numerous cases in Scotland.*

Evidence supplied by the Tuff-necks regarding Subærial Volcanic Action.—From the stratigraphical data furnished by the Basin of the Firth of Forth, it is certain that this region, during a great part of the Carboniferous period, existed as a wide shallow lagoon, sometimes overspread with sea-water deep enough to allow of the growth of corals, crinoids, and brachiopods; at other times shoaled to such an extent with sand and mud as to be covered with wide jungles of a lepidodendroid and calamitoid vegetation. As volcanic action went on interruptedly during a vast section of that period, the vents must sometimes have been submarine, but may at other intervals have been subærial. Indeed, we may suppose that the same vent might begin as a subaqueous orifice and continue to eject volcanic materials, until as these rose above the level of the water, the vent became subærial. I have not been able to determine which were submarine vents; but some interesting evidence may be collected to show that many actually rose up as insular cones of tuff above the surrounding lagoon.

The structure of the tuff in many necks suggests subærial rather than subaqueous stratification. The way in which the stones, large and small, are grouped together in lenticular seams may be paralleled in the slopes of many a modern volcano. Another indication of this mode of origin is supplied by the traces of wood to be met with in the larger tuff-necks. The vents of Fife and Linlithgowshire contain these traces sometimes in great abundance. The specimens are always angular fragments, the largest I have observed being a portion of a stem about 2 feet long and 6 inches broad, in the neck below St Monans church. They are frequently encrusted with calcite. In a neck to the west of Largo Law I found many pieces with the glossy fracture and clear ligneous structure shown by sticks of well-made wood charcoal. In another neck at St Magdalens, near Linlithgow, the wood fragments occur as numerous

* Quarterly Journ. Geol. Soc. 1860, p. 245.

black chips. So far as can be ascertained from the slices already prepared for the microscope, the wood is always coniferous. These woody fragments have not been found in the interstratified tuffs nor in the associated strata. They are specially characteristic of the necks. The trees from which they are derived grew, I believe, on the volcanic cones, which as dry insular spots would support a different vegetation from the club-mosses and reeds of the surrounding swamps. As the fragments occur in the tuffs which, on the grounds already stated, may be held to have been deposited within the crater, they seem to point to intervals of volcanic quiescence when the dormant or extinct craters were filled with a terrestrial flora, as Vesuvius was between the years 1500 and 1631, when no eruptions took place. Some of the cones, such as Largo Law, the Saline Hill, and the Binn of Burntisland, no doubt rose several hundred feet above the water. Clothed with dark pine woods, they must have formed a notable feature in the otherwise monotonous scenery of central Scotland during the Carboniferous period.

Relation of the visible Necks to the position of the original Volcanic Cones and the surrounding Sheets of Lava and Tuff.—From the facts above detailed, it is evident that in most cases the necks represent, as it were, the mere denuded stumps of the volcanoes. In some cases, indeed, denudation has not advanced so far as to lay bare the cones, which still consequently lie buried under subsequent accumulations. There must be many concealed cones of this kind in the region. In a few examples the progress of denudation has reached such a point that the cone can be partially made out amidst its surrounding masses of tuff. One of the most interesting of these is Largo Law, of which an outline has been given in fig. 2. The accompanying section (fig. 13) represents what

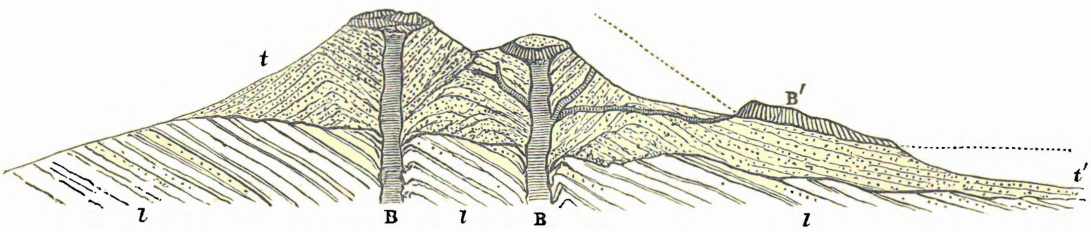

Fig. 13.—Section across Largo Law.

l, *l*, Lower Carboniferous strata; *t*, Tuff of cones; *t′*, Tuff of plain beyond the cones; BB, Basalt ascending vents and sending out veins; B′, Basalt which has probably flowed out at the surface. (See p. 467.) The dotted lines are suggestive of the original outline of the hill.

appears to me to be the structure of this hill. There are two conjoined cones, each of which was probably successively the vent of the volcano. The southern and rather lower eminence, as already mentioned, is traversed by rib-like dykes of basalt, which point towards its top, where there is a bed of the same rock underlying a capping of tuff. On its eastern declivity lies the basalt *coulée*, described on page 467. The higher cone is surmounted by a cake of basalt which, as I have above suggested, may have solidified at the bottom of the latest crater. Of course all trace of the crater has disappeared, but the general conical form of the volcanic mass remains. The upper dotted lines in the figure are inserted merely to indicate hypothetically how the volcano may originally have stood. On the west side, the sheets of tuff which were thrown out over the surrounding country have been almost entirely removed, but on the east and south they still cover an extensive area. (See fig. 1.)

Another excellent example of the connection between a conical neck and the surrounding masses of tuff and lava which proceeded from it is presented by the Binn of Burntisland, to which I have already alluded. A section across that eminence gives the geological structure represented in fig. 14. The dip of

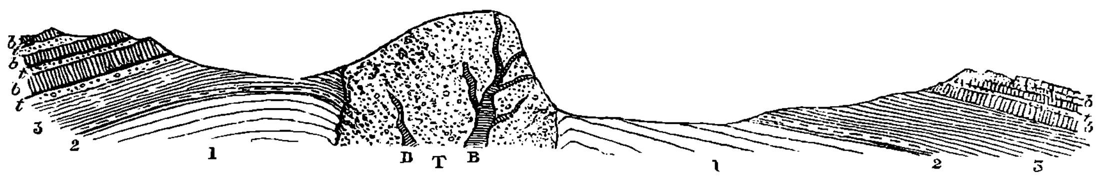

Fig. 14.—Section across the Binn of Burntisland.

1, Sandstones ; 2, Limestone (Burdiehouse) ; 3, Shales, &c. ; *b*, *b*, Interstratified basalts ; *t*, *t*, Bedded tuff, &c.; T, Tuff of the great neck of Burntisland ; B, Basalt veins.

the rocks away from the volcanic pipe at this locality has been produced long after the volcanic phenomena had ceased. The arch here shown is really the prolongation and final disappearance of the great anticlinal fold of which the Pentland Hills and Arthur Seat form the axis on the opposite side of the Firth. But if we restore the rocks to a horizontal, or approximately horizontal position, we find the Binn of Burntisland rising among them in two or perhaps more necks, which doubtless mark one of the centres of volcanic activity in that district. A series of smaller neck-like eminences runs for two miles westward.

Another remarkable instance of the connection of a volcanic pipe with the materials ejected from it over the surrounding country is furnished by Saline Hill in the west of Fife. That eminence rises to a height of 1178 feet above the sea, out of a band of tuff which can be traced across the country for fully three miles. Numerous sections in the water-courses show that this tuff is regularly interbedded in the Carboniferous Limestone series, so that the relative geological date of its eruption can be precisely fixed. On the south of Saline Hill, coal and ironstone, worked under the tuff, prove that this portion of the mass belongs to the general sheet of loose ashes and dust, extending outwards from the original cone over the lagoon in which the Carboniferous Limestone series of strata was being deposited. But the central portion of the hill is occupied by the volcanic pipe. A section across the eminence from north-west to south-east would probably show the structure represented in fig. 15. Immediately to the east of the Saline Hill lies another eminence, known as the Knock Hill, which marks the site of another eruptive vent. A coal-

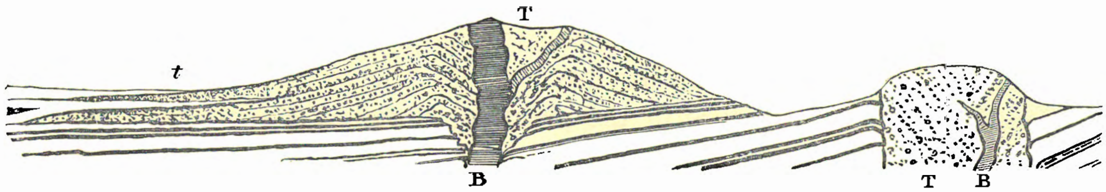

Fig. 15.—Section across the Saline Hills, Fife.

The thick parallel black lines mark the position of seams of coal and ironstone, some of which are worked under Saline Hill. T, Tuff of the necks ; *t*, Tuff at a little distance from the cone, interstratified with the ordinary sedimentary beds ; B, Basalt. The larger eminence is Saline Hill, the lower is Knock Hill.

seam (the Little Parrot or Gas Coal) is worked along its southern base, and is found to plunge down steeply towards the volcanic rocks. This seam, however, is not the same as that worked under the Saline Hill, but lies some 600 feet below it. Probably the whole of the Knock Hill occupies the place of a former vent.

Many additional examples might be cited of partially uncovered volcanic cones still surrounded by their ejectamenta. Probably in most cases the upper loose portion of a cone would be washed down as the general subsidence of the region brought it within reach of the water. Hence the crater would disappear, and only such rounded cones would remain as those which have been exposed once more to view by the removal of the overlying Carboniferous formations. The subjoined diagram (fig. 16) may serve to show the stages in the gradual re-emergence of these buried cones.

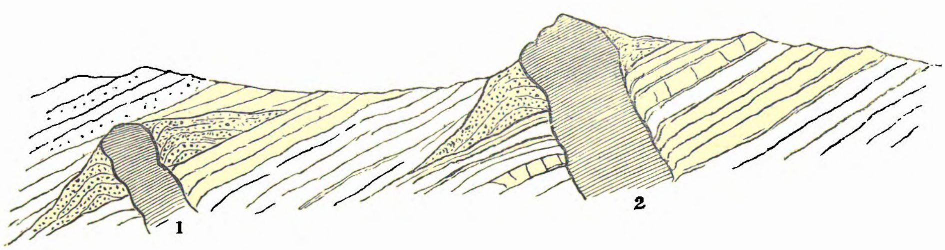

Fig. 16.—Diagram to illustrate how volcanic necks may be concealed and exposed.

1, Tuff and basalt neck, still buried under the succeeding sedimentary accumulations;
2, Tuff and basalt cone partially uncovered and denuded.

Final Stages of Volcanic Activity in the Tuff-necks.—After the explosions ceased by which the vents were opened and the cones of debris were heaped up, heated vapours would in many cases, as in modern volcanoes, continue for a long while to ascend in the vents. The experiments of DAUBRÉE on the effects of water and vapour upon silicates under great pressure and at a low red heat, have shown how great may be the lithological changes thereby superinduced. It is inconceivable, therefore, that the mass of tuff and lava lying deep within a volcanic vent, and thoroughly permeated with constantly ascending heated vapours, should escape some kind of change. I am inclined to attribute to this cause the frequent conversion of the sandstones round the walls of the vents into quartz-rock. The most remarkable example of metamorphism within the vent itself, which I have observed in the Basin of the Firth of Forth, occurs in the great vent of the Campsie Hills.* That remarkable volcanic orifice has been filled up with materials, some of which present the usual characters of coarse agglomerate, but with a more decidedly crystalline matrix. This crystalline texture increases here and there to such a degree that the rock assumes the aspect of some of the lavas of the district. Yet its original fragmental character is indicated not only by its gradual passage into unmistakable agglomerate, but still more by the occurrence in it of numerous blocks of sandstone more or less completely converted into quartzite. This local and unequal re-crystallization of the volcanic debris of the neck is the kind of metamorphism to be looked for as the result of the prolonged ascent of superheated steam under some pressure within the pipe of a volcano. I may add, that in this same neck numerous veins of a yellow or pink felsitic rock may be seen traversing the agglomerate, and extending also into the surrounding bedded porphyrite-lavas. The frequent highly silicated composition of the veins in the vents of the porphyrite regions is a remarkable and not very intelligible fact.

2. *Intrusive Sheets and Dykes.*

Throughout the Basin of the Firth of Forth, every division of the Carboniferous system has been invaded by intrusive sheets or dykes of crystalline igneous rocks. These masses may sometimes have been connected with the surface by vents or cracks up which a portion of the molten material rose. In most cases, however, they ought probably to be regarded as hypogene manifestations of volcanic action,—portions of lava which, unable to reach the surface, were forced between the bedding, joints, and faults of the strata. It will be shown in a later part of this Essay that they possess crystalline characters which serve to distinguish them from the superficial lava-streams or interbedded sheets.

General Characters.—The petrography of these rocks will be more particularly discussed in the second part of this paper. They consist almost entirely of rocks to which the names diabase, dolerite, and basalt may be applied. Occasionally they are of a felsitic nature. They include all the more crystalline and granitoid rocks of the region, though occasionally they present the ordinary close-grained black aspect of basalt. Their texture may be observed to bear some relation to

* See Explanation to Sheet 31, "Geological Survey of Scotland," par. 21 (1878), mapped by Mr R. L. JACK.

their mass, so far at least as that where they occur in beds only two or three feet or yards in thickness, they are almost invariably closer-grained. A cellular or amygdaloidal texture is hardly to be observed among them, and never where they are largely crystalline or granitoid. Differences of texture, however, may often be observed within short distances in the same mass, and likewise considerable varieties in colour and composition. As a rule, the most finely crystalline portions are those along the junction with the stratified rocks, the most crystalline occurring in the central parts of the mass. A diminution in the size of the crystalline constituents may be traced not only at the base, but also at the top of a sheet, or at any intermediate portion which has come in contact with a large mass of the surrounding rock. Salisbury Crags may be cited as a good example; another, and in some respects better, illustration is supplied by the intrusive sheet at Hound Point (fig. 17), to the east of South Queensferry, where some layers of shale have been involved in the igneous rock, which

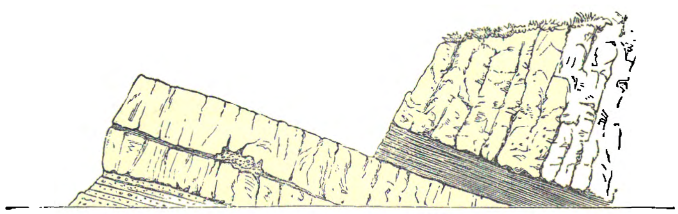

Fig. 17.—Intrusive sheets between shales and sandstones, Hound Point, Linlithgowshire.

becomes remarkably close-grained along the junction.* This change in texture and absence of cellular structure form a well-marked distinction between these sheets and those which have flowed out at the surface as true lava-streams.

Another characteristic of the intrusive sheets is the alteration they produce among the strata through which they have made their way, whether these lie above or below them. The strata are sometimes crumpled up in such a way as to indicate considerable pressure. They are occasionally broken into fragments, though this may have been due rather to the effects of gaseous explosions than to the actual protrusion of melted rock. But the most frequent change superinduced upon them is an induration which varies greatly in amount even along the edge of the same intrusive sheet. Sandstones are hardened into quartz-rock, breaking with a smooth clear glistening fracture. Shales pass into a kind of porcellante, jasper or Lydian-stone. Coals are converted into a soft sooty substance, sometimes into anthracite. These alterations, and the remarkable changes of texture experienced by the invading dolerites, will be again referred to in Part II.

Further evidence of the truly intrusive nature of these sheets is to be

* See Hay Cunningham's "Essay," p. 66, and plate ix., and "Geol. Survey Memoir on Geology of Edinburgh," p. 114.

found in the manner in which they catch up and completely enclose portions of the underlying or overlying strata. The well-known examples on Salisbury Crags (fig. 18) are paralleled by scores of other instances in different parts of the region. The subjoined woodcut (fig. 19) represents the way in which an intrusive sheet of a pale much altered rock involves shales in the Edinburgh district.

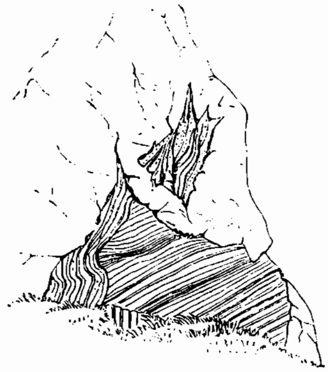

Fig. 18.—Intrusive dolerite sheet enclosing and sending threads into portions of shale, Salisbury Crags, Edinburgh.

Moreover, the sheets do not always remain on the same horizon; that is, between the same strata. They may be observed to steal across or break through the beds so as to lie successively between different layers. No more instructive example of this relation could be cited than that of the intrusive rock which has been laid open in the Dodhead Limestone Quarry, near Burntisland. As shown in the accompanying figure (fig. 20) this rock breaks through the limestone and then spreads out among the overlying shales, across which it passes obliquely. But when we trace the larger intrusive sheets this transgressive character is seen

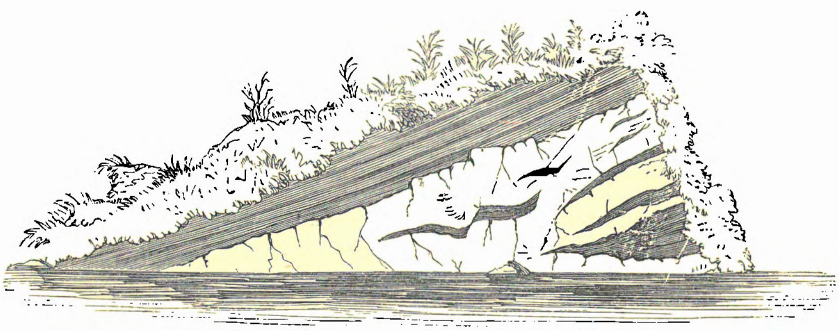

Fig. 19.—Intrusive sheet enveloping shales. Bed of Linhouse Water. "Geol. Survey Memoir of Edinburgh District," p. 115.

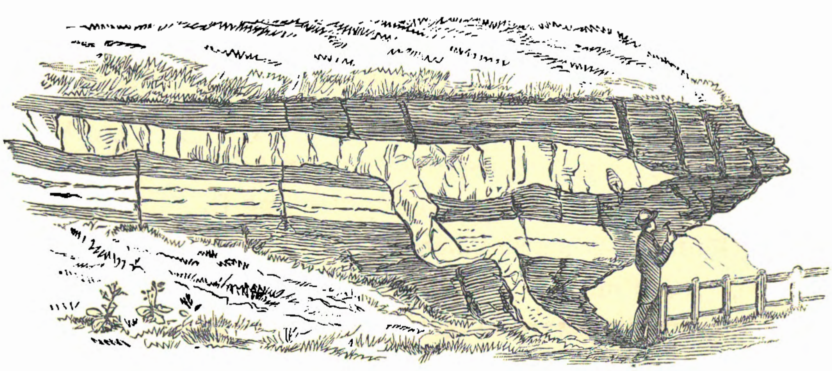

Fig. 20.—Intrusive sheet invading limestone and shale, Dodhead Quarry, near Burntisland.

to be sometimes manifested on a great scale. Thus, along the important belt of intrusive rocks that runs from Kilsyth to Stirling, the Hurlet limestone lies in one place below, in another above, the invading mass, but in the intervening ground has been engulphed in it. Similar evidence of the widely separate horizons occupied by different parts of the same intrusive sheet is supplied at Kilsyth, where the intrusive sheet lies about 70 or 80 fathoms below the Index Limestone, while at Croy, in the same neighbourhood, it actually passes above that seam.*

The thickness of the intrusive sheets varies within tolerably wide limits. They here and there dwindle down to an inch or less in thickness, running away as threads from some thicker mass. But they more usually form masses of considerable depth. The rock of Salisbury Crags, for example, is fully 150 feet thick at its maximum. That of Corstorphine Hill is probably about 350 feet. The great sheet which runs among the lower limestones from Kilsyth by Denny to Stirling has been bored through to a depth of 276 feet, but as the bore started on the rock, and not on overlying strata, some addition may need to be made to that thickness.

Area and Horizons.—Taking first the area of surface occupied by intrusive sheets apart from their geological horizons, we observe that the Falkirk and Stirlingshire coal-field is girdled with a great ring of these sheets. Beginning at the Abbey Craig, near Stirling, we may trace this ring as a continuous belt of high ground from Stirling to the River Carron. Thence it splits up into minor masses in different portions of the Carboniferous system, and doubtless belonging to different periods of volcanic disturbances, but yet sweeping as a whole across the north-eastern part of the Clyde coal-field, and then circling round into Stirlingshire and Linlithgowshire. There are no visible masses to fill up the portion of the ring back to Abbey Craig. But through the high grounds of Linlithgowshire a number of minor intrusive sheets form an eastward prolongation of the ring, taking in the masses near Edinburgh, and then bending northwards into Fife. In the latter county the intrusive masses acquire their greatest development. A nearly continuous belt of them runs from the Cult Hill near Saline on the west, to near St Andrews on the east, a distance of about thirty-five miles. This remarkable band is connected with a less extensive one, which extends from Torryburn on the west, to near Kirkcaldy on the east. It is remarkable that to the east of the axis of the Pentland Hills hardly any trace is to be seen of intrusive sheets.

If now we examine the geological position of the strata invaded by these intrusive masses, we find that by far the larger proportion forms part of the Carboniferous Limestone series. The belt between Stirling and Kilsyth keeps among the lower parts of that series. On the same general horizon are the great sheets of dolerite which stretch through Fife in the chain of the Cult, Cleish, and Lomond Hills on the one side, and in the eminences from Torryburn to

* Explanation of Sheet 31, "Geological Survey of Scotland," §§ 43 and 83.

Kinghorn on the other. In Linlithgowshire and Edinburghshire, as well as in the south of Fife, they traverse the Calciferous Sandstone groups. If the horizon of the sheets furnished any reliable clue to their age, it might be inferred that they were intruded during the earlier portion of the Carboniferous period. But on closer examination it will be observed, that the same intrusive mass sometimes extends from the lower into the upper parts of the Carboniferous groups. Thus, in the west of Linlithgowshire, a large protrusion which lies upon the upper limestones, crosses most of the Millstone Grit, and reaches up almost as high as the Coal-measures. Again, in Fife, to the east of Loch Leven, a spur of the great Lomond sheet crosses the Carboniferous limestone, disregards a large fault, and advances southward into the coal-field of Kinglassie. In Stirlingshire and Lanarkshire, numerous large dolerite sheets have invaded the Millstone Grit and Coal-measures, including even the upper red sandstones, which form the top of the Carboniferous system in this region.

Relation of the Intrusive Sheets to the Volcanic Centres.—Some light might be expected to be thrown on the age of the intrusive sheets by the manner in which they are related to the various centres of volcanic activity, but a satisfactory connection can hardly be established between them. Where the intrusive sheets reach their greatest development there are few, sometimes no trace of volcanic pipes, with their associated beds of tuff and streams of lava. On the other hand, in those tracts where volcanic orifices must have been active for long periods, intrusive sheets, when they occur at all, are commonly small and unimportant. In the case of a hill like Arthur Seat, where the lowest igneous rocks are intrusive sheets, and where the higher and larger mass consists of lavas and tuffs, erupted at the surface, we might speculate on the probability that the lower sheets of molten rock had been injected between the planes of the strata, either during some of the preliminary hypogene efforts, before direct communication had been established with the surface, or subsequently towards the close of the volcano's history, when that communication had become choked up. But in the case of the volcanic hills to the north of Burntisland, the intrusive sheets lie not below but above the interbedded lavas and tuffs, through which they come as irregularly as through ordinary sedimentary rocks. The most direct connection between volcanic pipes and large doleritic and basaltic sheets is to be seen in the east of Fife. To the north-east of Largo, for example, a plateau of this nature runs for a distance of four miles, with a breadth of about one mile. Round its margin are scattered upwards of a dozen small volcanic vents filled with tuff, and some of them partially with basalt. Its external characters exactly resemble those of many of the true intrusive sheets further west. But as no rock is found lying above it, it cannot certainly be affirmed to be itself an intrusive mass, though its internal structure, as revealed by the microscope, so entirely agrees with that of intrusive sheets, and differs from that of interbedded masses, that we may regard it as having been once covered by rocks under which it was injected. Since, however, isolated portions of columnar basalt occur in this and some of the neighbouring masses, we have probably to do with phenomena both of a hypogene and superficial character. These basalts may have flowed out at the surface from one or more of the surrounding vents, though the main sheets of dolerite were intrusive. This association of intrusive and interbedded masses round the same volcanic centre would be precisely analogous to that at Arthur Seat. The microscope furnishes a satisfactory means of discriminating between many of the intrusive and interbedded igneous rocks, as will be explained in the sequel.

Age of the Intrusive Sheets.—As the great epoch of volcanic activity in the Basin of the Firth of Forth extended from an early part of the Calciferous Sandstone period to near the close of the Carboniferous Limestone, it is probable that a large number of the intrusive sheets belong to some portion of that protracted series of volcanic eruptions. But some of them are certainly later than the latest known member of the Scottish Carboniferous system. These acquire a fresh interest and importance when viewed in connection with the evidence already given in this memoir regarding post-Carboniferous, or at least very late Carboniferous, volcanic action in Fife. For it is manifest that the phenomena were not confined to one small area. These late intrusive sheets cover a large area in Linlithgowshire and Lanarkshire. They reappear in Ayrshire, where the Coal-measures are likewise pierced with volcanic vents, and overspread with sheets of lava, tuff, and sandstone of Permian age. It is quite possible also, as I have already remarked, that some of the volcanic necks between the east of Fife and the heart of Ayrshire may belong to this late period. The later agglomerate of Arthur Seat has so exactly the character of some of the Permian necks of Ayrshire, that I suggested some years ago the probability of its being of the same age. More recently I have observed on Largo Law and others of the latest necks in the east of Fife, agglomerate precisely of the Arthur Seat type, which is coarser and redder, with more of the debris of the surrounding rocks, and less of the dirty-green diabasic matrix than the ordinary agglomerate of the older Carboniferous necks.

I have referred to the sheets of dolerite and basalt which in the east of Fife spread over considerable areas of the surface, and stand in evident relationship with the volcanic necks around them. In no material respect do they differ from the sheets which invade and overspread the upper Coal-measures in the great coal-field. In both cases they overlie the Carboniferous strata, and are not themselves covered by any later formation except glacial drift and other post-Tertiary deposits. All therefore that can be affirmed regarding them is that they are later than the youngest part of the Scottish Carboniferous system which they overspread unconformably. As a provisional arrangement, I would class them as probably of Permian date. That some, at least, are older than the Tertiary volcanic period is established by the fact, pointed out by me many years ago, that they are traversed by the great series of east-and-west Miocene dykes, though others in Stirlingshire may possibly be parts of an outflow from these dykes. For the reason, however, above given in regard to including the younger volcanic necks of Fife in this paper, I do not exclude these latest sheets.

Dykes.—Excluding the east-and-west Miocene dykes, there are comparatively few dykes in the Basin of the Forth save in connection with the volcanic necks, as already described. Among the red sandstones on which the city of Edinburgh is built, a number of dykes have been cut in draining, well-sinking, and other operations. Among the streams of the same neighbourhood an occasional dyke or vein may be seen traversing and involving the shales or sandstones. But the contact-phenomena do not call for any special remark in addition to what has been already said in reference to the intrusive sheets. Some of the curious features of internal structure presented by the dykes will be described in the Second Part of this Paper.

3. *Bedded Lavas and Tuffs.*

The minor cones in the region discharged in most cases only showers of tuff. Hence it is common to meet with beds of stratified tuff intercalated among the ordinary Carboniferous strata, without any other volcanic accompaniment. Numerous examples occur in Linlithgowshire and the western part of Edinburghshire, as well as in Fife. The tuff of these solitary beds is seldom coarse-grained. It usually consists of a fine dirty-green granular debris, derived from the trituration of the pyroxenic lavas of the period, and mixed with fragments of sandstone, shale, limestone, and other stratified rocks. It is often seamed with layers of ordinary sedimentary matter, probably indicating that its eruption did not occur at once, but was prolonged, with occasional pauses. The gradation of the upper part of the tuff into the overlying strata is often insensible, shewing that while the showers of tuff grew feebler, the usual sediment of the lagoon imperceptibly regained possession of the bottom.

From some of the larger or at least more close-set vents tuff continued to be thrown out for a long period, without the appearance of lava. The thick tuffs of Dunbar and North Berwick mark the earliest eruptions of the East Lothian district. The Saline vents threw out only tuff to a depth of several hundred feet. The numerous vents in the east of Fife likewise produced chiefly tuff, although lava certainly rose in many of them, if it did not actually escape at the surface in those wide sheets already noticed.

Lava-cones, answering to the solitary tuff-cones, do not appear to have existed. The lavas never occur without tuffs, except here and there where a number of successive flows lie piled one above another without visible trace of intercalated fragmentary layers (fig. 21). This, so far as can be observed, is

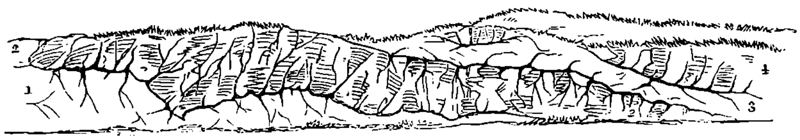

Fig. 21.—Section of four successive porphyrite lavas. East Linton, Haddingtonshire.

the case in the Garlton Hills, though more numerous exposures might show thin interstratified tuff bands. In the Campsie Hills also a considerable thickness of superposed lava-beds occurs without the intervention of any prominent tuff layer. These, however, are exceptional cases in this region, and they belong, as I have already pointed out, to a type of volcanic action which attained a great development during the time of the Calciferous Sandstones in the western and south-eastern parts of Scotland.

Leaving out of account the Campsie and East Lothian districts, in the other large accumulations of volcanic material, lavas and tuffs are interstratified with each other as well as with the ordinary sedimentary strata of the Carboniferous system. Perhaps the most complete and interesting example of this association is to be found on the coast between Burntisland and Kirkcaldy. The total thickness of rock in that section may be computed to be about 2000 feet. Of this amount it will probably be a fair estimate to say that the igneous materials constitute four-fifths or 1600 feet. The lavas vary in character from a black compact columnar basalt to a dirty green cellular or slaggy anamesite. They may average about 15 or 20 feet in thickness. Columnar and amorphous beds often succeed each other without any tuff. But along the junctions of the separate flows, layers of red clay, like the bole between the basalts of the Giant's Causeway, may frequently be noticed. The characteristic slaggy aspect of the upper parts of these ancient *coulées* is sometimes remarkably striking. It may be instructively contrasted with the close-grain of the upper and under margins of intrusive sheets.

Throughout the Basin of the Firth of Forth the basaltic lavas forming interbedded sheets, present external distinctions which serve to mark them off from the intrusive sheets. They are never so largely crystalline, nor spread out as such thick sheets; are frequently slaggy, amygdaloidal, fine-grained, and porphyritic; often decompose into a dull dirty-green fine-grained rock; and where they form a thick mass, are composed of different beds, of varying texture. The microscope confirms and extends these distinctions.

The number of intercalations of tuff in the admirable coast-section between Burntisland and Kinghorn is very great. Besides thicker well-marked bands, interstratified with the basalt beds, innumerable thin layers occur among the associated zones of sedimentary strata. The character of these tuff seams may be inferred from the following details of less than two feet of rock at Pettycur Point :—

Tuff,	1·5 inch.
Limestone,	0·2 „
Tuff,	0·5 „
Shale,	0·2 „
Tuff,	0·1 „
Shale and tuff,	1·0 „
Shale,	0·2 „
Limestone,	0·5 „
Shale full of volcanic dust,	3·5 „
Shaly limestone,	1·5 „
Laminated tuffaceous limestone,	2·0 „
Limestone in thin bands, with thin laminæ of tuff,	0·8 „
Granular tuff,	0·6 „
Argillaceous limestone, with diffused tuff,	0·9 „
Fine granular tuff,	0·7 „
Argillaceous limestone, with diffused tuff,	1·5 „
Laminated limestone,	0·1 „
Limestone, with parting of granular tuff in middle,	0·9 „
Tuffaceous shale,	2·0 „
Limestone,	0·4 „
Shaly tuff,	1·25 „
Laminated limestone,	0·1 „
Tuff,	1·2 „
	21·65 inches.

Such a section as this brings vividly before the mind a long-continued intermittent feeble volcanic action during pauses between successive outbursts of lava. In these intervals of quiescence the ordinary sediment of the lagoons accumulated and was mixed up with the debris, supplied by occasional showers of volcanic dust. Thin layers of sandstone, streaked with remains of the Carboniferous vegetation; beds of shale full of cyprid-cases, ganoid scales, and fragmentary ferns; thin beds of limestone, and bands of fireclay supporting seams of coal, are interleaved with strata of tuff and sheets of basalt. Now and then a sharp discharge of larger stones would take place, as in the case of the block described by me some years ago as having fallen and crushed down a still soft bed of coal.*

These volcanic eruptions, however, did not seriously interfere with the larger physical changes in progress over the whole region. Thus the depression

* "Geol. Magazine," vol. i. p. 22.

which led to the spread of a marine and limestone-making fauna over much of central Scotland affected also this volcanic district. The limestones extended over the submerged lavas and tuffs, which, however, in spite of the subsidence, continued for some time to be poured forth until the volcanic activity at last ceased, and the whole area went down beneath a deep mass of Carboniferous deposits.

Numerous illustrations might be taken from Linlithgowshire showing a similar volcanic progress contemporary with ordinary quiet sedimentation. Two examples may suffice, one presenting intercalations of tuff, the other associated bands of lava. In fig. 22, we observe at the base a black shale (1) of the usual type. It is covered by a bed of nodular bluish grey tuff (2) containing black shale fragments. A second black shale (3) is succeeded by a second thin band of pale yellowish fine tuff (4). Black shale (5) again supervenes, containing rounded fragments of tuff, perhaps ejected lapilli, and passing up into a layer of tuff (6). It is evident that we have here a continuous deposit of black shale which was three times interrupted by showers of volcanic dust and stones. At the close of the third interruption, the deposition of the shale was renewed and continued, with sufficient slowness to permit of the segregation of thin seams and nodules of clay ironstone round the decomposing organic remains of the muddy bottom (7). A fourth volcanic interlude now took place, and the floor of the water was once more covered with tuff (8). But the old conditions of deposit were immediately afterwards resumed (9); the muddy bottom was abundantly peopled with ostracod crustaceans, while many fishes, whose coprolites have been left in the mud, haunted the locality. At last, however, a much more serious volcanic explosion took place. A coarse agglomeratic tuff (10), with blocks sometimes nearly a foot in diameter, was then thrown out, and overspread the lagoon.*

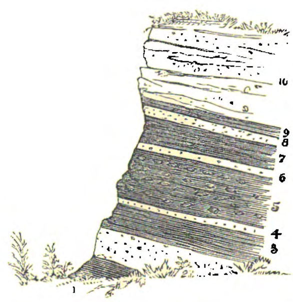

Fig. 22.—Section in old quarry, west of Wester Ochiltree, Linlithgowshire.—Calciferous sandstone series.

A second example from Linlithgowshire (fig. 23) brings before us a volcanic episode of another form in the history of the Carboniferous Limestone. At the bottom of the section a pale amygdaloidal, somewhat altered basalt-rock (A) marks the upper surface of one of the submarine lavas of that period. Directly over it comes a bed of limestone (B) fifteen feet thick, the lower layers of which are made up of a dense growth of the thin-stemmed coral *Lithostrotion irregulare.* The next stratum is a band of dark shale (C) about two feet thick, followed by about the same thickness of an impure limestone with shale seams (D). The conditions for coral and crinoid growth were evidently not favourable, for this argillaceous limestone

* See "Geological Survey Memoir of Edinburgh," p. 45.

was eventually arrested first by the deposit of a dark mud, now to be seen in the form of three or four inches of a black pyritous shale (E), and next by the inroad of a large quantity of dark sandy mud and drift vegetation, which has been preserved as a sandy shale (F), containing *Calamites, Producti,* ganoid scales, and other traces of the life of the time. Finally, a great sheet of lava, represented by the uppermost amygdaloid (G), overspread the area, and sealed up these records of Palæozoic history.*

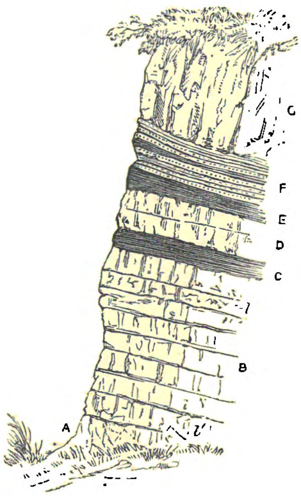

Fig. 23.—Section in Wardlaw Quarry, Linlithgowshire.

A final example may be cited of the regular alternation of lavas and tuffs with each other, and with ordinary sedimentary accumulations. The well-known Calton Hill of Edinburgh consists of the succession of rocks shown in the subjoined section (fig. 24). The great mass of the hill is made up of beds of porphyrite, representing true superficial lava-currents (Nos. 1, 5, 7, 9, 11, 13, 15). With these are intercalated bands of nodular tuff, and occasional seams of shale and sandstone, more or less charged with volcanic detritus (Nos. 2, 4, 6, 6′, 8, 10, 12, 14). The whole

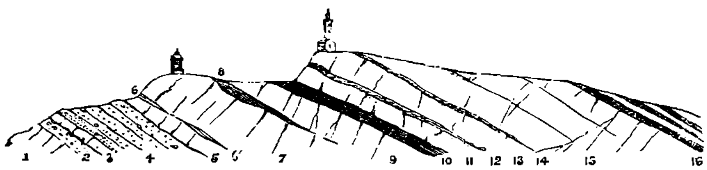

Fig. 24.—Section of Calton Hill, Edinburgh.

of this thoroughly volcanic series of rocks passes conformably under the Calciferous sandstones and shales shown at the right hand of the diagram.

As the interstratified lavas and tuffs were laid down in sheets at the surface, they necessarily behave like the ordinary sedimentary strata, and have undergone with them the curvatures and fractures which have affected this region since Carboniferous times. Notwithstanding their volcanic nature, they can be traced and mapped precisely as if they had been limestones or sandstones. This perfect conformability with the associated stratified rocks is strikingly seen in the case of the great sheets of lava which, as I have already said, lie imbedded in the heart of the Borrowstounness coal-field. The overlying strata having been removed from their surface for some distance, and the ground having been broken by faults, these volcanic rocks might at first be taken for irregular intrusive bosses, but their true character is that shown in fig 25,

* See "Geol. Surv. Mem., Geology of Edinburgh," p. 58.

where by a succession of faults, with a throw in the same direction, the upper basalts of Bonnytoun Hill are gradually brought down to the level of the sea.

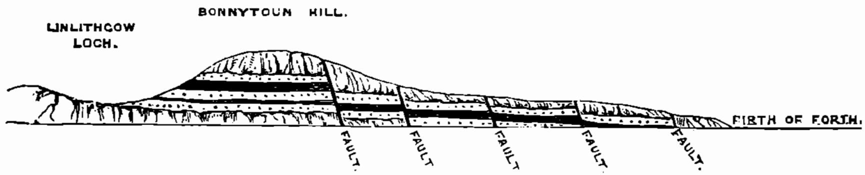

Fig. 25.—Section from Linlithgow Loch to the Firth of Forth.

Among the ancient volcanic phenomena of the Basin of the Firth of Forth, mention may, in conclusion, be made of the evidence for the former existence of thermal springs and saline sublimations or incrustations. Among the tuffs of North Berwick a fetid limestone has been quarried, which bears indications of having been deposited by springs, probably in connection with the volcanic action of the district. The rock has the peculiar carious wavy structure with minute mamillated interstices so common among sinters. It contains minute grains of iron-bisulphide and flakes of white kaolin, which probably represent decayed prisms or tufts of natrolite. The lower limestones of Bathgate furnish abundant laminæ of silica interleaved with calcareous matter, the whole probably due to the action of siliceous and calcareous springs. Some portions of the limestone are full of cellular spaces, lined with calcedony.* In a recent communication to this Society, I described the discovery of a saline water among the volcanic rocks to the west of Linlithgow. A bore was sunk to a depth of 420 feet without reaching the bottom of these rocks. The water that rose from it was found to contain as much as 140 grains of chloride of sodium in the gallon. It is not improbable, as I have suggested, that this salt was originally produced by incrustations on the Carboniferous lavas immediately after their eruption, as has happened so often in recent times at Vesuvius, and that it was then buried under the succeeding showers of tuff and streams of lava.†

* "Geol. Survey Memoirs," *op. cit.* p. 49, *et seq.*

† "Proc. Roy. Soc. Edin." vol. ix. p. 367.

[PART II.

PART II.—PETROGRAPHY.

In the following section of this Memoir I propose to offer a sketch of the general results of a somewhat extended investigation of the characters revealed by the microscope in the various igneous rocks of the Basin of the Firth of Forth. A few of the more accessible rocks of the region have been microscopically examined and described by several observers, more especially by Mr ALLPORT, in whose interesting communication on British Carboniferous dolerites an account in particular is given of some of the igneous masses round Edinburgh.* But no attempt has yet been made to compare the minute structure of the volcanic rocks as a whole, and in connection with the history of volcanic action in the region, and to determine the leading types of composition and arrangement.

During the last twelve years I have devoted much time to the study of the microscopic characters of the crystalline rocks of Scotland. One portion of this inquiry has embraced an examination of the volcanic rocks described in the foregoing part of the present Memoir. I have had thin sections prepared of about 350 rocks from all parts of the region, illustrating every variety of composition and texture encountered by me in the field.† These sections present a most instructive picture of the original diversities of the volcanic masses, as well as of the alterations which their internal structure has subsequently undergone. The details which they furnish are full of interest, and I hope to publish them elsewhere. But a *resumé* of the chief results as yet arrived at in the course of the investigation may appropriately find a place as a sequel to the stratigraphical narrative in the preceding pages.

For the purpose of petrographical classification, as well as of stratigraphical detail, volcanic rocks may be arranged in two great leading subdivisions. I. The Crystalline, embracing all which have been erupted to the surface or intruded below in a molten condition; and II. The Fragmental, including all which have been thrown out in a fragmentary form. The former may be termed briefly the Lavas, and the latter the Tuffs.

I. THE CRYSTALLINE ROCKS OR LAVAS.

Looked at in their petrographical aspect as they occur among the Carboniferous formations of the Basin of the Firth of Forth, the Crystalline rocks or Lavas may be arranged into four chief groups—1st, Augite-felspar Rocks,

* "Quart. Journ. Geol. Soc." vol. xxx. p. 529.

† These sections have been excellently prepared, in the petrographical laboratory of the Geological Survey of Scotland, by A. MACCONOCHIE and R. LUNN.

embracing all the basalts, anamesites, dolerites, and diabases, and thus by far the most abundant rocks in the region; 2d, Olivine-augite-serpentine Rocks, hitherto observed only in two localities; 3d, Felspar-magnetite Rocks, consisting of the "porphyrites," which played so important a part among the earlier eruptions of the Carboniferous period; 4th, Felsitic Rocks, consisting of a few intrusive veins or dykes.

A. Augite-Felspar Rocks.

These crystalline masses play a chief part in the igneous phenomena of central Scotland. They present three recognisable types of structure, which however pass by insensible gradations into each other,—1st, The Diabases or granitoid type; 2d, The Dolerites; 3d, The Basalts.

I. The Diabases or Granitoid Type. (Plate XI. figs. 1 and 2).

1. *General External Characters.*—The rocks embraced in this group are thoroughly crystalline in structure, and usually remarkably coarse in texture. Some of their individual crystals measure occasionally an inch in length. They vary in colour partly with the tint and proportion of the felspar, and partly with the degree of alteration which they have undergone. Some varieties have a mottled pink hue, from the flesh-coloured felspar; most are more or less distinctly greenish, from the decay of their magnesian silicates, and consequent diffusion of saponite, delessite, or other secondary product. They are never amygdaloidal, nor ever porphyritic, though here and there crystals considerably larger than those of the general mass may be observed. They always occur as intrusive masses, generally in sheets or amorphous bosses. They have manifestly been intruded at some depth from the surface among the Carboniferous rocks, and have never flowed above ground in lava-streams. Examples of this type are found among the hills to the west of Edinburgh. Lindsay's Craig near Kirkliston, Crossall Hill near Dalmeny, Muckraw near Torphichen, Auchensteary near Kilsyth, Croy, and the Carron Water above Denny, may be cited as localities where it is well displayed. But most of the coarsely crystalline intrusive sheets throughout the Lothians show the characters of this type more or less distinctly.

2. *Microscopic Characters.*—The structure is essentially crystalline. In many slices no trace of any ground mass can be made out between the separate crystals. Here and there a small proportion of a dull, minutely granular or microfelsitic substance may be detected between crossed Nicols. Most of the rocks, however, have been considerably altered, and many alteration-products appear between the still recognisable original crystals. It is possible that there may have been at first in some of the varieties a glassy or felsitic

magma, which is no longer recognisable. The chief component minerals are orthoclase, plagioclase, augite, titaniferous iron, and apatite. The general aspect of these rocks is represented in figs. 1 and 2, Plate XI.

The felspars usually constitute the main mass of the rock; but sometimes the augite is nearly equally abundant. Next in amount comes the iron. The proportion of the apatite varies within wide limits, being sometimes limited to infrequent stout prisms, at other times diffused in abundant minute needles.

The orthoclase, in the more typical examples, occurs to the almost total exclusion of any triclinic felspar. It is always somewhat kaolinised, but fresh portions may often be observed. It occurs macled in the Carlsbad form, and often shows its characteristic divergent herring-bone lineation from the plane of twinning. The alteration has resulted in the production of a finely granular substance, which between crossed Nicols appears dusted over with bright and coloured points, representing, doubtless, the silicic acid of the original felspar. The orthoclase prisms are frequently crowded with minute needles and larger hexagonal prisms of apatite, either promiscuously through the whole felspar, or directed from the exterior towards the centre, which may remain comparatively clear. In the more decomposed rocks the orthoclase has acquired a yellowish hue from diffused limonite.

The triclinic felspar, in the coarser and more typical varieties, is probably never labradorite. It differs from the characteristic labradorite of the dolerites and basalts in being less finely striated, and much more liable to decomposition. It often presents a milky appearance, which under a high power is resolved into a fine kaolinised substance. So generally is it decomposed, that though the external form of its prisms may remain distinctly marked off from the surrounding ingredients of the rock, no unaltered portions may remain, or if they occur they lie in small insular spaces amidst the surrounding granular kaolin. In proportion as the orthoclase diminishes, the triclinic felspar appears to increase. In the less largely crystalline varieties, however, it ceases to present itself as the milky, kaolinised albite-like mineral, but takes the usual water-clear well striated form of the labradorite, so characteristic of the typical dolerites and basalts of the region.

Augite is certainly the most conspicuous mineral under the microscope. This arises not only from its abundance in most of the rocks, but from its frequently and remarkably undecomposed aspect. Its freshness even in the presence of zeolites, "viridite," and other proofs of considerable alteration, is not a little singular. It is found in definite crystals of the usual eight-sided forms met with among igneous rocks; though the prisms are usually imperfect and are sometimes twinned, good cleavage angles of 87·6′ are common. The augite may sometimes be observed enclosing prisms of the milky or finely granular triclinic felspars, which shoot through it and are wrapped round by it, showing that the augite has crystallised later than the felspar. As a rule the augite is tolerably free of extraneous substances. It is usually much cleaved and cracked, with occasional cavities either empty or filled with some decomposition product. Its most frequent endomorphs are needles and distinct hexagonal prisms of apatite. Thin rhomboidal plates of titaniferous iron are also occasionally to be noticed. The colour of the augite varies from a pale port-wine tint to a pale greenish brown in the fresh state. Here and there, even in the comparatively unchanged mineral layers of a dirty green or brown decomposed substance, may be noticed in the internal cavities, or coating with a thin film the sides of the minute fissures. This is doubtless a product of decomposition of the augite itself. Every stage may be followed, from the first appearance of change until all trace of recognisable augite has disappeared, its place being taken by a mass of opaque brown and green amorphous earthy matter. In some varieties of rock the augite almost disappears. This may be observed in portions of the intrusive sheet west of Denny, where the rock consists mainly of orthoclase.

Olivine has not been certainly detected by me in any rocks of this type. Its presence may indeed be suspected from the serpentine so frequently to be noticed among the ingredients. But in no case have I ever observed any definite boundaries to the serpentine enclosures such as to indicate the outlines of olivine crystals. This is the more remarkable, as in many of the dolerites of the region which are quite as much altered as the rocks now under description, the olivine, though entirely serpentinised, still shows very distinctly the original outline of its crystals and granules. If any olivine ever existed in these coarsely crystalline intrusive rocks it must, I think, have been in very small quantity, and probably in granular indefinite aggregates rather than in homogeneous defined crystals.

Titaniferous iron is always present, and often in most interesting forms. Its fragmentary rhombohedra are scattered abundantly throughout the substance of the rock, sometimes enclosed in the augite and felspar, but usually independent. It frequently assumes the form of thin rhombohedral plates, which may now and then be observed to lie apart but parallel with each other, in obedience to original crystallographic force. There is a tendency not seldom to be observed, in these detached plates, to build themselves together into the framework of a crystal. Beautifully perfect skeleton rhombohedra of this kind may be seen in the rock of Crossall Hill, near Dalmeny (see fig. 26). Viewed by transmitted light, no structure can be made out in the individual crystals or lamellæ, though here and there they may be seen associated with the peculiar milky white *leucoxene* which sometimes, indeed, as DE LA VALLÉE POUSSIN and RENARD have shown in the case of the Belgian plutonic rocks, replaces the opaque iron in part or the whole of a crystalline face.

When, however, reflected light is employed, the velvet-black colour of the titaniferous iron, its semi-metallic lustre, small conchoidal fracture, and cleavage lines can be admirably seen. By this means also we ascertain that many apparently homogeneous masses of titaniferous iron have cavernous centres, more or less completely filled with pyrite. Amorphous particles of the same iron oxide also occur. Possibly these may conceal some magnetite. But the latter mineral has not been identified in any determinable crystalline forms among these rocks.

Fig. 26.—Skeleton rhombohedron of titaniferous iron, Crossall Hill, Dalmeny (magnified 20 diameters).

Apatite is probably never wholly absent, though its proportions vary within remarkably wide limits. In such very coarsely crystalline rocks as that of Crossall Hill, it occurs in colourless but somewhat dusty stout hexagonal prisms, sometimes 2·5 millimetres in diameter. It may there be seen shooting across from an augite into a felspar crystal without fracture, whence we may infer that at least in these portions of the rock there could have been but little motion of the mass at the time of crystallisation of the minerals. In other varieties of rock, such as that of Ratho, the apatite is crowded in the form of minute and perfectly clear hairs through the felspar.

In one or two examples quartz appears as an original constituent, in the form of small blebs. This is well shown in the case of the remarkable sheet of intrusive rock which has invaded the Carboniferous Limestone series in the valley of the Carron Water above Denny. The quartz appears there as occasional clear particles between the abundant kaolinised felspars, decayed titaniferous iron, and sparse, much altered augite. It contains numerous fluid cavities and small microlites. In most cases however, quartz, when present, is full of clouded impurities, contains no fluid cavities, and is aggregated in forms characteristic of this mineral as a secondary product.

As the rocks of the type now being described have all undergone more or less alteration, secondary products abound in them. Many of these form conspicuous features in the large veins and cavities to be seen in the quarry or natural section. Calcite, prehnite, pectolite, analcime, have long been known from these masses, and fine specimens, particularly of pectolite, have been obtained from Ratho and Corstorphine. Examined under the microscope, nearly every slice exhibits more or less of the amorphous brown and green earthy substance already referred to. This may be seen investing the augite and penetrating its fissures. But it also occurs diffused through rocks in which this mineral still remains fresh. It is not, therefore, produced by all varieties of augite, and is no doubt in a large number of instances due to the decay of some other minerals. Where it abounds the titaniferous ore is usually greatly oxidised, streaks and diffused grains or blotches of hæmatite, but more frequently of limonite, being abundant.

Serpentine or some serpentinous product is a frequent constituent of the rocks. It occurs of a pale apple-green colour ranging to dirty brownish green, is sometimes finely fibrous in tufted or plumose forms, and shows the characteristic aggregate polarization. In some rocks, that of Corstorphine for example, it occupies interspaces comparable in size to those of some of the original minerals. It might in such cases represent former olivine, but, as I have already stated, I have never detected it in rocks of this type retaining any outward crystalline form. It may sometimes be noticed in threads running through fissures, both of the augite and felspar. But the visible change of augite into serpentine is not common in any of the rocks which I have examined.

Besides the serpentine there occurs, sometimes in considerable quantity, a green translucent substance, occupying spaces between crystals, filling up cavities in the crystals themselves, and spreading in frequent filaments through minute fissures of this rock. In some instances it assumes beautifully fibrous, crested, and vermicular forms. Probably delessite and saponite are both included in these green alterations. According to the recent analyses of Dr Heddle, the green hydrous minerals of these volcanic rocks do not comprise chlorite, which he says is distinctively a mineral of the crystalline schists.

Plates of brown biotite appear in the more altered rocks, and minute prisms of hornblende occur under similar conditions. I have never observed any epidote. Pyrite is rarely altogether absent.

Calcedony in minute amygdules and strings is not infrequent among the more decayed varieties of rock, but crystalline quartz is the usual form in which the free silica has been deposited among the interstices of the rock. These quartz patches are distinguished from the original blebs of that mineral by the characters above specified, more particularly by the amount of impurities they contain, the absence of fluid cavities, and by the minutely flecked or aggregated structure which they present between crossed Nicols.

Arranged in the order of durability, the essential mineral constituents of these rocks would stand as follows:—The apatite remains singularly fresh, even in the midst of thoroughly kaolinized felspar. The quartz, where it occurs, is of course also unimpaired. Augite and titaniferous iron are about equally well preserved; where the one shows signs of alteration the other is usually also affected. The felspars have been almost invariably attacked, every stage being observable from the pellucid crystal to the dull granular kaolin. The green and brown decomposition products may represent in part minerals no longer recognisable.

From the description now given it will be seen that the largely crystalline intrusive sheets in the Basin of the Firth of Forth possess characters which do not admit of their being classed without some qualification in any established petrographical genus. From the dolerites they are marked off by the frequent preponderance of orthoclase and the presence of free quartz. From normal diabase they are also distinguished by their proportion of orthoclase, though undoubtedly they approach most closely to this rock, and I have retained this name as a generic designation for them. In many respects they remind one of augite-andesite. They show a similar mixture of monoclinic and triclinic felspars with augite, and a sparing quantity of free quartz. In judging of their relations to other rocks we must remember that they are always intrusive sheets, that in many cases they have caught up, and seem actually to have dissolved into their substance portions of the rocks through which they have been injected, and that as a fact they show very considerable differences of composition even within short spaces in the same mass. The proportions of the felspars, the relative abundance of the titaniferous iron and augite, the size and number of the cavities filled with alteration-products, all vary greatly from point to point.

Bearing these gradations in mind, we cannot be surprised to find that no line of demarcation can be drawn between the coarsely-crystalline orthoclase-bearing diabases and the dolerites to be immediately described. Varieties of rock occur which, according to the feature in their composition most kept in view, might be referred to either group.

II. The Dolerites. (Plate XI. Fig. 3.)

Under this title I have since the year 1867 classed the dark crystalline-granular augitic sheets by which the Carboniferous rocks of central Scotland have been invaded, and which were previously embraced under the term "greenstone."* Though the word "dolerite" has been restricted by German petrographers to rocks of Tertiary and post-Tertiary date, I was unable to discover any difference between those associated with the Carboniferous rocks and those which in the Inner Hebrides are certainly of Tertiary age. The opportunities for a comparison between them were many and favourable. I traced the probable connection of the numerous east and west "trap-dykes" which traverse Scotland, with the great Miocene lava-plateaux of the Inner Hebrides, and showed that these dykes, cutting as they do through all the known palæozoic and secondary rocks, including parts of the Tertiary volcanic sheets, and even across the latest faults of the country, were almost certainly of

* Sheet 14, "Geological Survey, Scotland, Dec. 1868," and Explanation of same.

Tertiary age. They consist of undoubted and typical dolerite. They run across some of the great igneous sheets in the Coal-measures, and can there be admirably compared with the older rock. After examining them over a wide area in the field, and having had many slices cut from both series of rocks for microscopic investigation, I could never distinguish between them except by reference to their respective labels. Accordingly, I gave up this term greenstone in favour of dolerite, and this change has been adopted in all the subsequent publications of the Geological Survey in Scotland.

My friend, Professor ZIRKEL, who visited me in Ayrshire, and went over some of the evidence on the ground, came to the conclusion that no difference was to be made out by the microscope between the Carboniferous igneous rocks and those of Tertiary date.* Mr ALLPORT has come to the same conclusion.†

But while no recognisable distinction can be drawn between Carboniferous and Tertiary dolerites, I have been led to discover that a definite line of demarcation can be drawn between the intrusive dolerites and the augitic lavas which have been erupted at the surface. On a former page (*ante*, p. 481) I have referred to some of the broad external features of difference. But the microscope helps still further to discriminate them, and furnishes a valuable assistance in this respect to the labours of the geologist in the field. So reliable indeed are the microscopic tests, that I believe it is possible, in most cases at least, to affirm, even from the small portion of rock placed under the microscope, whether the parent mass consolidated beneath ground or at the surface.

Chemically there is probably, as a rule, little or no difference between the intrusive and interbedded sheets. Their differences lie in structure and texture, and point to the opposite conditions under which the rocks acquired solidity. While the intrusive sheets are conspicuously crystalline dolerites, the interbedded are essentially basalts of varying degrees of compactness. I would, therefore, restrict the term dolerite to the one, and basalt to the other petrographical group.

1. *General External Characters and Mode of Occurrence.*—In fresh undecayed specimens the texture of dolerite is markedly crystalline, passing into crystalline-granular. The component minerals can usually be distinguished either with the naked eye or a lens, the triclinic felspar appearing in clear glassy finely-striated prisms in the dark green or black base of augite and titaniferous iron. Hence the rock commonly presents a dark-grey speckled appearance. Where alteration has made progress, brown tints prevail on the outer crust, and the rock crumbles into a brown or even yellow sand, as its iron is converted into limonite.

An intrusive sheet is hardly ever amygdaloidal; when amygdules do

* "*Mikroskopische Beschaffenheit der Mineralien und Gesteine*," 1873, p. 291.

† "Quart. Journ. Geol. Soc." *ut supra*.

appear they are small in size and limited in their range through the rock. It is distinguished by a peculiar uniformity of texture, seldom showing any large porphyritic crystals, such as frequently occur in the basalts. In some rare cases it may be columnar, but the columns are large and rude when compared with those of the basalts. The edges of a sheet where it approaches the contiguous strata present a much finer grain than the central portions. Small veins of this compact variety may occasionally be found penetrating the adjoining rocks, which are usually much indurated, both above and below intrusive sheets.

Rocks presenting these characters abound in this region; the great sheets traversing the Lanarkshire and Stirlingshire coal-field, those in the heart of Fife, and many of those in the West of Mid-Lothian may be taken as illustrations.

2. *Microscopic Characters.*—As above remarked, no sharp line can be drawn between these rocks and the diabases already described. The dolerites, however, seldom contain any orthoclase or any original quartz, and are never so coarse in texture. They show a remarkably crystalline structure under the microscope. In many varieties no distinct trace of any glassy ground-mass can be detected. In others this substance appears as a clear pale yellow or green limpid glass, crowded with dark trichites, and sometimes with minute green transparent microlites and needles of apatite.

The felspar is triclinic, and appears in clear colourless striated prisms sometimes half an inch long. It is probably labradorite; it can at least be easily distinguished from the milky translucent variety so common among the diabases. It sometimes contains minute glass enclosures, and is often studded with apatite needles, or crossed by stouter prisms of that mineral. Small dark grains, which may be titaniferous iron or magnetite, may likewise be observed. Not infrequently a remarkable finely fibrous, transparent, or translucent substance may be observed encrusting the felspar. It resembles the occurrence of a zeolite. Occasionally a detached portion of augite may be detected entirely enclosed in the clear felspar. But there can be no doubt that the latter mineral was the first to crystallise into definite prisms. Traces of orthoclase are comparatively infrequent, but a clear or a kaolinized prism twinning in the vertical axis may now and then be detected.

The augite occurs in large well-defined crystals, in irregular kernels, and rarely in minute granules. In most of the dolerites, particularly in the coarser varieties, it presents a fractured or flawed structure as in the diabases, and not uncommonly it might be supposed to have been penetrated across its figures by intrusive prisms of felspar. Beautiful examples of this relation of the two minerals may be noticed in the dolerites of the Falkirk and Slamannan coal-field. Examination with polarised light, however, shows that the apparent dislocations are at least in a vast majority of cases deceptive. What seem to be severed parts of one crystal with wedges of felspar between them, are then found to polarise on the same plane, and in short to belong to one undisturbed crystal which formed round and enclosed the already completed network of triclinic felspar prisms. Hence in one part of a slide we have one of these prisms completely enveloped in an augite crystal, while in an adjoining portion of the same preparation the augite seems to be completely enclosed within the felspar. There can be no doubt that, as above remarked, on the whole the felspar took crystalline form first. This is admirably shown in the contact-phenomena to which I shall afterwards refer. At the same time, there are occasionally indications that minute granules of augite in the original molten rock did form definite crystals before the crystallisation of the felspar was completed.

There is one distinctive feature between the mode of occurrence of the augite in the dolerites and in the interbedded anamesites and basalts which I have found to hold good, with few exceptions. While in the intrusive sheets the augite occurs either in well-marked crystals or in large crystalline irregularly-shaped portions, in the superficial lava-beds it is commonly present in abundant small granules and in sparse definite crystals. The granulated form has never been noticed by me in the dolerites, save in a few cases where the rock may have been almost superficial, or where it has been rapidly chilled by contact with the rocks through which it has been intruded. This point will be further described in the section treating of the interbedded basalt-rocks.

Apatite is present in most of the rocks, though extremely variable in amount. It assumes the form of fine needles and of stouter hexagonal prisms, but never attains the size it reaches in the diabases.

The opaque ferruginous mineral seems to be chiefly titaniferous iron. Distinct rhombohedral forms in thin lamellæ may often be noticed, and not infrequently with the same tendency to build themselves into crystallographic forms, which I have already noticed. But minute grains showing octohedral faces occasionally reveal the presence of magnetite.

Olivine is rarely recognisable, even as a serpentinous pseudomorph, and never in the freshly crystalline state. There is no greater contrast between the dolerites and the basalts than the part which this mineral plays in them respectively. In some dolerites small serpentine enclosures retain what are probably the outlines of former olivine grains and crystals. But these are small in size, and very vaguely characterised when contrasted with those which remain to be described in the basalt group.

Some of the more salient characters of the dolerites are represented in fig. 3, Plate XI., which shows the structure of a portion of the rock of Dalmahoy Hill, Edinburgh.

The alteration of the dolerites has produced results closely similar to those above described as occurring in the diabases. The triclinic felspar, though often singularly unchanged, may be detected passing into the granular kaolinised condition. The augite, as in the diabases, remains on the whole less affected than the felspar. It may, however, be observed with a surrounding border sometimes of an opaque black, sometimes of a dirty brown substance, which graduates inward into the still fresh augite. In other instances the external decomposed coating consists of serpentine, and strings of the same mineral may be traced along the fissures of the augite. The decomposition into serpentine may also be observed to have occasionally begun in the centre, while the surrounding part of the augite still remains tolerably fresh. Much diffused green matter, the so-called "viridite," may represent both olivine and augite. Leucoxene occurs under the same conditions as in the diabases. Hæmatite and limonite have often replaced the original iron oxides. Pyrite is almost always present in minute grains. Calcite, various zeolites, quartz, and calcedony fill up the pores and cavities of the rocks, and often run in veins through them.

Phenomena of Contact.—It is well known that an intrusive crystalline rock assumes a close texture along its junction with the rocks through which it has been thrust, and that these in turn commonly show more or less induration. I have examined a large number of microscopic sections taken both from the igneous and aqueous rocks, and will state here the general results of the investigation.

Tracing the variations of an intrusive dolerite outwards in the direction of the rocks which it has invaded, we perceive change first in the augite. The large crystals and kernels of that mineral grow smaller until they pass into a granulated form like that characteristic of basalts. The large plates and amorphous patches of titaniferous iron or magnetite give place to minute particles, which tend to group themselves into long club-shaped bodies. The labradorite continues but little affected, except that its prisms, though as defined, are not quite so large. The interstitial glassy ground-mass remains in much the same condition and relative amount as in the centre of the rock. In figs. 11 and 12 of Plate XII., I have drawn the structure of two interesting examples of contact phenomena.

Along the line of contact with a sandstone or other granular rock, the dolerite becomes exceedingly close-grained. Its felspar crystals are still quite distinct even up to the edge of the stratified rock, but are fewer in relative number, and still smaller in size, though an occasional prism two or three millimetres in length may occur. They retain also their sharpness of outline, and their comparative freedom from enclosures of any kind. They tend to range themselves parallel with the surface of the sandstone. The augite exists as a finely granular pale green substance, which might at first be taken for a glass, but it gives the characteristic action of augite with polarised light. It is intimately mixed through the clear glass of the ground-mass, which it far exceeds in quantity. The iron oxides now appear as a fine granular dust, which is frequently aggregated into the elongated club-shaped objects just referred to, as if round some inner pellucid or translucent microlite. In patches throughout the field, however, the oxides take the form of a geometrically perfect network of interlacing rods. This beautiful structure, described and figured by ZIRKEL and others,* is never to be seen in any of the dolerites, except close to the line of contact with the surrounding rocks. It occurs also in some of the dykes. (See Plate XII., fig. 12).

I have not succeeded in detecting any microlites in the sandstones at the edge of a dolerite sheet, though I have had many slices prepared for the purpose. The sandstones, so far as my observations go, do not offer any proofs of alteration capable of satisfactory elucidation by the microscope.

Where dolerite has invaded sandstone there is usually a tolerably sharp line of demarcation between the two rocks. It is seldom easy to procure a hand-specimen showing the actual contact, for the stone is apt to break along the junction-line. Where, however, the rock traversed by the igneous mass is argillaceous shale, we may find a thorough welding of the two substances into each other. In such cases the dolerite at the actual contact shows a still further degree of diminution in its component particles. It becomes a dark opaque rock, which in thin slices under the microscope is found to be formed of a mottled or curdled segregation of exceedingly minute black grains and hairs in a clear glassy matrix, in which the augite and felspar are not individualised. But even in this tachylite-like rock perfectly formed and very sharply defined crystals of triclinic felspar may be observed ranging themselves as usual parallel to the bounding surfaces of the rock. These characters are well seen in the contact of the intrusive sheet of dolerite with shale and sandstone at Hound Point, described on p. 475.

Another instructive example is furnished by the small threads which proceed from the dolerite of Salisbury Crags, and traverse enclosed fragments of shale. Some of these miniature dykes are not more than $\frac{1}{8}$th of an inch in diameter, and may therefore easily be included, together with part of the surrounding rock, in the field of the microscope. The dolerite in these ramifications assumes an exceedingly fine texture. The felspar is the only mineral distinctly formed into definite crystals. It occurs in prisms, sometimes $\frac{1}{5}$th of an inch long, and therefore readily recognisable by the naked eye. These prisms are perfectly shaped, contain abundant twin lamellæ, and show enclosures of the iron of the base. They had been already completely formed at the time of injection; for occasionally they may be observed projecting beyond the wall of

* *Op. cit.* p. 273; Vogelsang's "Krystalliten."

the vein into the adjacent shale or sandstone, and they have ranged themselves parallel to the sides of the vein.* The black ground, from which these large well-defined crystals stand out prominently, consists of a devitrified glass, rendered dark by the multitude of its enclosed black opaque microlites. These are very minute grains and rudely feathered rods, with a tendency to group themselves here and there into forms like portions of the rhombohedral skeletons of titaniferous iron already described. Numerous green serpentinous granules may mark the position of the original augite. There is no trace of olivine.

So thoroughly fused and liquid has the dolerite been at the time of its injection, that little threads of it, less than $\frac{1}{100}$ of an inch in diameter, consisting of the same dark base, with well-defined felspars, may be seen isolated within the surrounding sedimentary rock. Minute grains and rounded portions of the latter may also be noticed in the marginal parts of the dolerite.

With regard to the change superinduced upon stratified rocks in the examples now under description, it is not easy to speak precisely, because the altered portions are completely enclosed within the mass of dolerite, and we cannot tell whence they were derived. They have acquired externally a percellanite aspect, and show numerous shining granules of quartz. Under the microscope this altered rock, which is pale grey or white, has a milky translucent finely granular or dusty base, reminding one of the base of a felsite. It contains thin layers of quartz pebbles, which are also scattered promiscuously through the more compact portions. I have not succeeded in detecting any microlites in this rock, save that here and there, close to its junction with the igneous threads and veins, it sometimes contains exceedingly minute cubes and irregular grains of a black opaque mineral. The quartz grains contain cavities, but are not clear, owing to the presence of many fine fissures and enclosed greenish matter. They may be seen projecting into the dolerite, which has moulded itself to them, and has sometimes detached and completely enveloped them.

It is evident that specimens taken from the edge of an intrusive sheet, where the rock has rapidly chilled and solidified, represent to us an earlier stage in

* The infusibility of the felspar has been well shown in some recent experiments on the rocks of the neighbourhood of Edinburgh. At my request, Dr R. S. MARSDEN has subjected some of these rocks to fusion at the laboratory of the University of Edinburgh, and I have had microscopic sections prepared of the products obtained. The basalt of Lion's Haunch is peculiarly instructive. Its large labradorite crystals have resisted the intense white heat which, continued for four hours, has reduced the rest of the minerals to a perfect glass. We can thus well understand how large definite crystals of felspar should have appeared in dykes and veins while the rock was still thoroughly liquid. The glass obtained from the Lion's Haunch rock is of a honey-yellow, and contains translucent tufted microlites. The iron forms beautiful dendritic films in the cracks. Altogether, the glass presents a strong resemblance to the peculiar substance found in some of the tuffs of the vents to be afterwards described. I am at present engaged in a series of experiments on the fusion of volcanic rocks and artificial slags, and hope to communicate the results in a future paper to the Society.

the history of the whole mass than specimens taken from its central portions. In fact, a series of samples collected at short intervals from the outer contact to the inner mass shows, as it were, the successive stages in the consolidation of the molten rock.

From the observations just described, it appears that the triclinic felspars began to assume the shape of large definite crystals before any of the other minerals. These felspars already existed when the molten mass forced its way among the shales, for they can be seen lying with their long axes parallel to the surface of shale, precisely as, in the well known fluid structures, they behave round a large crystal imbedded in the heart of a rock. But most of the felspar remains still undividualised, together with the other constituents, in a dark glassy tachylitic magma. A few feet from where the consolidation was not so rapid, we perceive that the iron oxides grouped themselves into incipient crystalline forms and skeleton crystals; the felspar crystals formed abundantly, though small in size, and the augite was left as a finely granular green transparent substance. Still further towards the interior of the mass the normal character of the dolerite is gradually assumed.

One of the most constant kinds of alteration is that which affects dolerites and basalts where they have been intruded among carbonaceous shales or coals. A thin slice of the "white trap" from one of these junctions shows a dull white or pale yellowish granular translucent ground-mass, with a few small and decayed felspar prisms scattered through it. The absence of the usual green colouring matter and of the dark iron oxides is very marked under the microscope. The latter minerals seem to have been usually converted into siderite and limonite. The augite no doubt existed originally only in the minutely granulated form, but it cannot now be distinguished in the general kaolinised base.

III. The Basalts. (Plate XI. figs. 4 and 5.)

Under this title I include all those rocks of the augite-felspar series which have a compact or finely granular base, through which the component crystals of triclinic felspar (probably always labradorite) augite, olivine, and magnetite are crowded. This base consists partly of a clear or pale-brown glass ground-mass, and partly of minutely granulated augite, and microlites probably of the felspar. It varies much in amount, sometimes almost disappearing; at other times occupying by far the largest bulk of the rock, and with only a few scattered crystals of the usual minerals, as in some of the most compact homogeneous basalts.

The more distinctly crystalline varieties are anamesites. The great majority are, however, true basalts. Though there is no essential distinction between these two varieties, the term anamesite may be retained as a convenient synonym for those coarser basalts, where the felspar in well-defined crystals plays a leading part.

1. *General External Characters and Mode of Occurrence.*—The basalts are broadly distinguished from the dolerites by their greater closeness of texture, darker colour, tendency to assume a regular columnar form, frequent slaggy and amygdaloidal character, and their association with tuffs as interbedded sheets in the Carboniferous system. The more compact varieties break with a splintery conchoidal fracture, are iron-black on the fresh surface, and appear to consist of a homogeneous dull substance, in which only here and there a few shining crystalline facettes can be seen. From this extreme graduations can be traced to a distinctly porphyritic texture, where the same dark base is crowded with crystals, among which prisms of labradorite, and augite and grains of olivine can be seen with the naked eye. The beautiful anamesite of Craiglockhart Hill, near Edinburgh, contains well-formed crystals of augite of the usual form, sometimes half an inch long, and crystals of serpentised olivine nearly as large.

The action of the weather, however, has greatly altered the external aspect of the basalts. In some cases, especially where columnar, they weather spheroidally, but instead of the thick coating of decayed shells so common among the dolerites, they may be found with merely a thin yellow crust, below which the rock appears fresh and black. Where they are amorphous, and especially where amygdaloidal, they decompose with a very characteristic dirty green aspect. Alternations of these two modes of weathering may be observed even in the same cliff, as at King Alexander's Crag, near Burntisland, where the bedding of the basalts can be descried even from a distance by means of the difference.

The basalts occur chiefly as interbedded sheets. With the exception of the porphyrites, all the lavas poured out at the surface in the Basin of the Firth of Forth during the Carboniferous period were basalts. The hills between Bathgate and Linlithgow, those of Burntisland in Fife, and of the neighbourhood of Edinburgh, offer good examples.

But the basalts assume also an intrusive form. So far as I have observed, they have never been thrust in great sheets among previously formed rocks; at least the rock so thrust has not consolidated in the form of basalt. They occur abundantly, however, as small veins and dykes in the neighbourhood of volcanic vents. They are as evidently due to the superficial operations of volcanic action, as the dolerites are to those of a more deep-seated kind.

2. *Microscopic Characters.*—Several distinct and very characteristic types of structure are revealed by the microscope among the basalt-rocks in the Basin of the Firth of Forth.

(1.) The more distinctly crystalline basalts or anamesites are well illustrated by the rocks of Craiglockhart Hill (see fig. 4, Plate XI.), and the Long Row, near Edinburgh. When a thin section of one of these rocks is placed under the microscope, the first mineral to arrest attention is the abundant and fresh triclinic felspar. It forms the predominating ingredient, occurring in prisms with perhaps an average thickness of ·002 inch, and a length of about ·03 to ·05 inch. Occasional large porphyritic crystals ·1 inch and upwards in length may be seen. This mineral has frequently enclosed globular grains of augite, and minute octohedra or irregular particles of magnetite. With a high power it may be seen to be sometimes full of fine clear glassy spicules. Beautiful fluid structure is shown by the arrangement of the thin felspar prisms round some of the larger included crystals.

The augite comes next in abundance to the felspar; indeed, it sometimes equals if it does not actually exceed it in quantity. This mineral is likewise well preserved. It occurs in two distinct forms:—1st, As minute granules without crystalline contours, but with the rounded drop-like form so characteristic of many basalts. This is the predominant condition. 2d, As large admirably definite prisms of the customary forms. These, as previously stated, are sometimes half an inch long, and can be seen projecting from some of the weathered faces of the rock at Craiglockhart Hill. The zonal growth structure is beautifully displayed by some of these augites. I have observed in a few instances, that though the external form is sharply defined by a continuous band of the mineral, the interior presents a granulated appearance, as if it consisted merely of a congeries of the augite granules. In the Craiglockhart rock some of the augites may be seen nearly unflawed, while others immediately adjacent are entirely granulated. The latter portions, however, polarise uniformly as a whole, and not according to the individual granules. Small crystals of felspar, grains of magnetite, and portions of the ground-mass may be observed between the granules, which are of larger size than the average of those in the ground-mass.

The olivine is almost always readily apparent. In some of the rocks it appears in crystals easily seen with the naked eye, some of them indeed, as at Craiglockhart, reaching a length of more than $\frac{1}{4}$ inch. I have never observed it in small grains like the augite. It occurs in two conditions—(*a*) In sharply defined crystals, with easily measurable angles. When in this form, it contains few or no endomorphs, and has been able to resist alteration better than in the other form. Some of its central portions may be found still clear, and showing the proper reaction with polarised light. But its borders are altered into a pale greyish or greenish white substance which also traverses the centre along fissures. This substance polarises like serpentine, and is doubtless a serpentinous alteration-product. (*b*) In the usual, somewhat rounded, ill-defined crystals and grains. In this condition the olivine is often full of magnetite grains and crystals, and is generally completely altered into a yellowish-green serpentinous substance. This is the ordinary mode of occurrence of the mineral.

The magnetite occurs in octohedra, averaging perhaps ·001 inch in diameter, also in many larger and irregular aggregations. Some of the latter, however, may be titaniferous iron. Apatite appears rarely in slender needles.

Between these recognisable minerals there lies a minutely granular base, which can be resolved by a high power chiefly into augite, with here and there traces of a dusty devitrified substance. But it cannot be called a glassy ground-mass. The proportion in which it occurs to the rest of the constituents is so small that the crystalline granular character of the rock remains conspicuous.

(2.) The true basalts vary greatly in details, but agree in the following general characters. The triclinic felspar occurs in minute prisms (perhaps on an average ·0005 of an inch thick and ·005 of an inch long) seldom in large porphyritic crystals. The augite appears in its two forms, but while the granulated condition is always present, the larger definitely shaped crystals are often absent. The olivine, always in serpentinous pseudomorphs retaining the rude contour of the original mineral, frequently lies in large porphyritic crystals. Magnetite forms a conspicuous feature, though its proportional amount is subject to great variations. The structure of the rock is always minutely granular, the granules consisting of augite; but between them, and in the wedge-shaped angles between the felspar prisms, a clear glass with pellucid spicules may sometimes be observed. (See fig. 5, Plate XI.)

The felspar is on the whole the predominant mineral, but this chief part is not infrequently taken by the granular augite. As in the dolerites, the felspar encloses globules of augite often less than ·0001 of an inch in diameter, also specks of magnetite. In fresh specimens it remains exceedingly clear and quite unchanged. It is always well striated. In some rocks its minute prisms are arranged in the most perfect fluid structure along the faces of the large olivines and augites. A good example of this arrangement is supplied by a very compact basalt on the shore to the west of Pettycur.

The augite granules average perhaps about ·001 of an inch in diameter. On applying a high power to their examination they are often seen to have imperfect crystalline outlines. That they are crystalline bodies, and not mere glass, is shown by their behaviour under polarised light. In some basalts—those of Kirkton, near Bathgate, for example—they appear as it were curdled together in irregular clots, with interspaces of a clear isotropic ground-mass. This tendency to segregation, however, has sometimes been in obedience to crystallographic force, for in the same district the granules are occasionally found in rings, the external outlines of which are rudely those of augite prisms, while the interior is occupied by a confused mass of augite granules, magnetite, and the general ground-mass of the rock. The colour of the granulated augite, under a low power, appears as a pale port-wine tint; but in thin slices, and with a high power, it is a pale brown or yellow, though the pink hue is not always lost even there. Perfect crystals of this mineral occur in some basalts; the most remarkable example in this respect with which I have met is from one of the dykes on the shore at St Monans, where, through a granular augitic base, regular prisms often twinned, are dispersed in great abundance, and admirably fresh. If minute petrographical subdivisions of the basalts were desirable, we might arrange in one series those where the felspar is greatly preponderant, and in another those where granular augite is the leading mineral.

The olivine varies much in quantity. In some basalts it appears only in occasional rare and small pieces; but usually it is discernible in every thin slice, and in some it forms a notable object even to the naked eye. It is always more or less converted into the usual green serpentinous substance. In certain basalts, especially in that of Mid Tartraven, Linlithgowshire, the olivine is occasionally so crowded with magnetite that this mineral forms by much the largest proportion of a crystal. The external form of the olivine remains distinct, however, and the altered serpentinous pseudomorph seems to bind the opaque octohedra together. In some of the Fife olivines the outer border is converted into a deep orange-yellow transparent strongly dichroic substance.

The magnetic iron appears in two forms. In the great majority of the basalts it assumes its usual form of minute octohedra, the shining triangular faces of which are well brought out by reflected light. But in some peculiar basalts the iron exists as minute thin lamellæ, which recall those of the diabases and coarse dolerites. From the angles obtained, however, and from the absence of the usual white porcelain-like accompaniment of titaniferous iron, I infer that these thin plates are magnetite. Basalts with this character occur at Pettycur in Fife, and also on the island of Inchkeith. Apatite is not recognisable.

The alteration of the basalts has always begun by the conversion of the olivine. Where much of this mineral is present, the decay of the rock produces the greenish hue so common among the interbedded sheets. The other minerals resist weathering for a long time, but the felspar is eventually kaolinised, the augite passes into a dark brown earthy substance, sometimes into serpentine, and the magnetite is oxidized into hæmatite, or more usually limonite.

It will be seen that in general arrangement of structure, these Carboniferous basalts of central Scotland exactly correspond with felspar basalts described by ZIRKEL from Germany, Faroe, Iceland, and the United States,* as well as with those of Tertiary age collected by him in Scotland. The endeavour to establish

* See his *Basalt-Gesteine*, 1870, and "Report of Geol. Explor., 40th Parallel, Microscopical Petrography" (vol. vi.), p. 229. Washington, 1876.

a petrographical distinction between the older and younger basalts breaks down completely when the rocks of the Basin of the Firth of Forth are brought in evidence. In their behaviour in the field, and quite as much in their structure under the microscope, they cannot be discriminated from these of Tertiary date. The specimen from Strathblane which was described by ZIRKEL as a good example of an abundant type of true basalt, is an intrusive boss among the Carboniferous rocks, and is almost certainly of lower Carboniferous age.

IV. SERPENTINE-OLIVINE ROCKS.

Pikrite. (Plate XI. fig. 6.)

As an appendix to the normal dolerites and basalts, I insert here an account of a very remarkable and beautiful rock of rare occurrence in the Basin of the Firth of Forth. It is intimately associated with these rocks, and has evidently proceeded from some of the same vents. I know it as yet from only two localities—Blackburn, near Bathgate, and the island of Inchcolm. It appears to agree most closely with some of the rocks from the Fichtelgebirge, described by GÜMBEL under the name of "Pikrite."

1. *General External Characters and Mode of Occurrence.*—The variety from Blackburn occurs in that interesting belt of ground which runs southward through the Linlithgow and Bathgate Hills into the county of Mid-Lothian. This tract contains the records of a prolonged volcanic activity, during which lavas and tuffs were thrown out to a united depth of many hundred feet. The earliest eruptions began before the commencement of the deposition of the Carboniferous limestone series, and continued until the greater part of that series had been formed. As I have already stated, the lavas consist of basalts and amygdaloidal anamesites, the basalts being often singularly fresh, while the more coarsely crystalline rocks, especially where amygdaloidal, are often much decomposed. The volcanic ridge descends somewhat abruptly into the low grounds at its southern end. This arises apparently from several causes. A large fault with a downthrow to the south strikes eastward from the Bathgate coal-field, and skirts the southern base of the hills. The volcanic rocks are thus thrown down on the south side. Besides this, as the vents of eruption seem to have lain to the north, the accumulated sheets of lava and tuff no doubt thinned away in a southerly direction. Moreover, a vast amount of sandy and gravelly drift and of underlying boulder clay has been laid down over the lower grounds. That the volcanic rocks, however, continue southward is proved by numerous bores which have been sunk through the drifts in search of coal. They rise to the surface near the village of Blackburn, and after another interruption from the depth of glacial detritus are seen in the channel of the River Almond, whence they may be traced southwards for about two miles further. The sections in that stream, as well

as in the Briech Water, instructively show how rapidly the volcanic sheets diminish southwards. Of the vast mass of basalt and tuff intercalated between the lower limestones, most of that to the east of Bathgate has disappeared. It is the upper or later portion of the volcanic series, lying above the Main Limestone, which is prolonged southwards into Mid-Lothian, its position being indicated by the thin limestones between which it is intercalated.

At Blackburn one of the old lavas of a very peculiar kind has been quarried for many years as a material termed "lakestone," employed for the construction of the soles of ovens, owing to its capability of withstanding the effects of considerable heat. The rock is seen only at the quarry itself. It is there found to present a beautifully ice-worn upper surface, lying under a mass of stiff dark boulder-clay. In the channel of the Almond Water, immediately below the rock, some shaly sandstones and shales occur, with a thin seam of crinoidal limestone lying upon a few inches of coal. These strata dip towards the north-west at 25°, and the volcanic sheet has a similar inclination. It is evidently a bed intercalated in the limestone series. Its precise stratigraphical relations are made clear by a section in the Skolie Burn, less than two miles further south. A rock of a similar character, and quarried for the same purpose, is there exposed under a group of calcareous shales and thin limestone. Its upper part is in some places a fine slaggy amygdaloid. The strata lying directly upon it are of a peculiar green felspathic sandstone or shale, containing detached fragments of the amygdaloid, and likewise *Lingula* and other mollusca. It is clear that the rock is not an intrusive sheet, but is a true lava-bed, which was erupted and solidified at the surface during the accumulation of the older part of the Carboniferous Limestone series of West Lothian.

I am thus particular regarding the geological relations of this rock, because it stands at present as a nearly unique example of a very interesting variety of these Carboniferous lavas, and likewise offers a striking petrographical difference between the upper and under part of the same bed, such as I have not been able to discover anywhere else.

The rock is best displayed at the Blackburn Quarry. Looked at from a short distance, it appears to be one of the rudely jointed, somewhat decomposed brown or dirty-green doleritic or diabasic rocks of the district, with a tendency to weather out into spheroids. Examined more closely, the upper portion is seen to bear out this first impression, though evidently to present more decided traces of serpentisation than is usually to be observed. A specimen taken from the lower body of the stone would be termed a highly serpentinous diabase, nearly approaching a serpentine in outward aspect. Veins of serpentine and chrysotile, sometimes six inches thick and often streaked with calcite, run in vertical divisions through the whole rock. There is no line of demarcation to be drawn between the higher and lower parts of the rock. They cannot indeed be discriminated except by actual fracture and inspection, the whole mass appearing as one and indivisible. The upper part is too hard to be worked with profit, and is therefore thrown aside, but the workmen cannot fix any line below which the stone becomes valuable, except by the ease with which it yields to their tools.

A few hand-specimens, selected from various parts of the upper harder band, give the following characters:—Finely crystalline base of a dirty, blackish green colour, and a tolerably homogeneous but dull texture, showing many ill-defined greenish white points, apparently of decayed felspar, with minute facettes, some of which are pyrite; fracture, splintery; hardness, 3 to 4.

The variety from Inchcolm was brought to my notice by one of my students in the University, Mr ERNEST ADY, who landing on the island, and being struck with the external aspect of the rock, took specimens, and sliced them for the microscope. It occurs in beds, under which lie some hardened sandstone, limestone, and shale. It seems to be an intrusive mass, as are those of the adjacent islands and the neighbouring coast of Fife. It is rather coarsely crystalline-granular. Even to the naked eye its honey-yellow grains of olivine, dark glancing crystals of augite, occasional plates of glistening brown biotite, and serpentinous interstitial matter, are quite apparent. But under the microscope it becomes an object of surpassing beauty.

2. *Microscopic Characters.*—The lower portion of the Blackburn rock consists chiefly of serpentine. This mineral occurs in (1) irregular patches, the edges of which are sometimes sharply defined against the other ingredients, while elsewhere they seem entangled among the latter; (2) in more definite forms, which are almost certainly those of former olivine; (3) in tufts and fibrous streaks; and (4) in veins of true chrysotile. Between the abundant portions of serpentine traces of a pale mineral full of serpentinous veins, which behaves like olivine in polarised light, are probably the last recognisable remnants of that mineral, which at first appears to have constituted the main part of the rock. Large, much-flawed crystals of a pale brown to claret coloured mineral are scattered through the serpentine, and are enclosed in the less altered olivine. These answer to augite in general behaviour with polarised light, but I have been unable to obtain any satisfactory cleavage angles. Numerous needles and fine prisms of apatite are crowded into some parts of the rock. Abundant iron black particles of titaniferous iron or magnetite occur, and a little pyrites. A few prisms of triclinic felspar also occur. There is no distinct ground-mass separate from the general base of serpentine.

The upper portion of the Blackburn rock presents a marked contrast in its minute structure. It contains among its constituents a feeble quantity of a distinct glass which occurs occasionally in large interspaces, and then shows a dusty character, resolvable with a high power into exceedingly minute dark globules.

The most abundant mineral is a colourless and tolerably fresh triclinic felspar. Next in amount is a pale yellowish transparent mineral in very small prisms, which seems to be augite, but of an unusual form. Some of these prisms, not exceeding ·0005 of an inch in diameter, may be seen enclosed in the altered olivine. The latter mineral can be recognised in the form of crystals, from about ·03 to ·10 of an inch in length, completely serpentinised. They consist mainly of a pale delicate apple-green clouded and fibrous substance, which is bordered and traversed by strings of a bright grass green, sometimes of rich yellowish brown. But these olivines occur in much smaller quantity than in the lower part of the rock. Titaniferous iron or magnetite likewise appears as in that lower part, but also in less abundance. Apatite may be detected occasionally. (See fig. 6, Plate XI.)

Without at present entering further into the detailed structure of this beautiful and interesting rock, the facts just stated show that in the lower half there is a preponderance of the heavy olivine, augite, and iron, while in the upper half the lighter felspar predominates. As I have said, it is quite impossible to draw any line between the two portions of the rock thus differently constituted. It is one indivisible mass, in which the lower part, a serpentine (representing olivine), shades up into the higher part, rich in felspar. In this case there has evidently been a separation of the ingredients according to their respective gravities, during the period when the mass was still in a molten condition, as SCROPE pointed out in modern lavas. The fluidity of the rock must have been such as to allow of this segregation even after the lava had moved some way along the surface.

The Inchcolm rock is considerably fresher than that of Blackburn. Examined under the microscope, it is seen to be by far the most beautiful rock in the Basin of the Firth of Forth. The olivine, its most abundant mineral, is still in large measure quite undecomposed, though frequently presenting the usual external crust and transverse wavy threads of green serpentine. Large pieces of fresh olivine give the characteristic reaction with polarised light. Next in quantity comes the augite, which is likewise singularly fresh. It has in thin slices a pale claret colour, and gives cleavage angles of 87° and 93°. It occurs in large well-defined prisms of the usual forms, often enclosing grains and crystals of olivine. A milky felspar, full of fissures, filled with decomposition products, but still showing traces of twin lamellation, occupies a very subordinate place in the rock. Long scales of rich brown biotite occur here and there; also a few plates and grains of probably titaniferous iron. One of the most conspicuous ingredients is a rich emerald-green to grass-green product of decomposition, which fills up interstices, and running in veins and irregular streaks or tufts through the rock, gives a singularly bright tone to the field of the microscope. Other pale or colourless aggregates, sometimes distinctly fibrous, likewise occur. These various decomposition products give between crossed Nicols sometimes the reaction of serpentine, sometimes the pale milky blue tint and aggregate polarisation so often found in chlorite. Zeolitic fibrous tufts occur in some of the cavities. I have not observed any apatite.

B. Felspar-Magnetite Rocks.

The Porphyrites. (Plate XII. figs. 7 and 8.)

Under this title I provisionally group those Carboniferous volcanic rocks which in the Basin of the Firth of Forth have been mapped as "felstones," "porphyrites," and "claystones." They present very great varieties of external aspect, but possess certain common characters which suffice to enable the field-geologist to distinguish them from the basalt series. Occupying a definite place in the Carboniferous system in Scotland, they belong entirely to the great volcanic epoch at the beginning of the Carboniferous period. They form the thick-terraced masses which range through the north of Ayrshire, Renfrewshire, and Dumbartonshire to the Forth at Stirling. They partially appear at Edinburgh, in the Calton Hill and Arthur Seat, but on a much more extended scale in the Garlton Hills of Haddingtonshire. Similar rocks in Berwickshire, Roxburgh, and Dumfries spread over wide areas at the base of the Calciferous Sandstones. They are thus the oldest and most generally distributed of the volcanic rocks associated with the Carboniferous system in Scotland. In most essential characters they agree with the lavas so copiously erupted in central Scotland during the time of the Lower Old Red Sandstone, with which in another memoir I shall again discuss them. They thus belong essentially to an older as well as a more vigorous volcanic type than the basalts. Even the thickest and most extensive series of basalt eruptions, such as those of the Burntisland and Linlithgowshire districts, are of trifling amount when compared with the enormous sheets of bedded porphyrite in the Campsie and Ayrshire Hills.

The porphyrites always occur as contemporaneous or interbedded sheets, save in those comparatively infrequent cases where they have filled up the volcanic funnels, and now appear in necks.

1. *General External Characters.*—A "porphyrite" is marked by a dull close-grained porphyry base, through which are usually scattered crystals of a triclinic, less commonly an orthoclase, felspar. The base is usually of some shade of red or brown, varying from a dark chocolate or purple tint to pale yellow or nearly white, greenish and bluish shades being less common. It is frequently amygdaloidal. As a rule, the porphyrites are somewhat altered, fresh specimens being in many cases unobtainable, or only with much difficulty. The weather-

ing has particularly attacked the iron oxide in the rocks, hence the frequent red, brown, and yellow tints.

An important feature of the porphyrites as compared with the basalts is their comparative lightness. Their average specific gravity is about 2·6 to 2·7, while that of the basalts is about 2·9, a difference which is appreciable even when specimens are held in the hand. Some intermediate varieties, however, helping to connect the porphyrites with the basalts, are not always easily distinguished by external tests.

2. *Microscopic Characters.*—The distinguishing mark of the porphyrites under the microscope is the character of their ground-mass. It appears as a clear, colourless substance through which vaguely defined prisms of triclinic felspar are crowded. Between crossed Nicols it presents a characteristic mottled structure, the light and dark parts shading off insensibly into each other. As the slide is rotated the mottling wanders over it, every portion becoming successively light and dark (see Plate XII. figs. 7 and 8). This continues to be the case even with a high power. In a very few cases only have I noticed small interspaces which remained persistently dark. Colourless hairs or fine rods are not infrequent; and occasionally minute pale yellow or nearly colourless globules, which polarise like the globular augite of the basalts, may be observed.

This clear anisotropic ground-mass can scarcely be anything else than a felspar. It blends so insensibly with the felspar prisms, that where the defined forms of these prisms cease it is impossible to separate their substance from the surrounding mass. This is the case with most of the Garlton Hill porphyrites. In some cases the prisms are well striated, and stand out more definitely. I have attempted to delineate the structure in the drawings above referred to.

The felspars chiefly occur in these vaguely outlined forms. But in many porphyrites they appear also as large porphyritic crystals with exceedingly sharply marked boundaries. In the majority of cases they are triclinic, and probably labradorite. Now and then clear twins of orthoclase are to be observed. Among the Garlton Hills the larger felspars are occasionally crowded with enclosures, sometimes promiscuously diffused through the crystal, at other times in lines along the planes of twinning. The most abundant enclosures are minute globules of augite, not infrequently elongated into rod-like bodies. In one or two cases I have noticed numerous perfectly black opaque globules. These may be augite crowded with magnetite dust.

Taking the clear ground-mass as felspar, and including with it the recognisable felspar crystals, we find that perhaps about nine-tenths of the substance of one of the most typical porphyrites is felspathic. Next in abundance is magnetite, which occurs in recognisable octohedra, not infrequently imperfect, and in irregular shred-like particles. Its crystals are often extremely minute; in some of the rocks of the Garlton Hills they are on an average less than ·001 of an inch in diameter. In these microscopic grains, however, we can easily see with reflected light the glancing triangular faces of the octohedra, and the sub-conchoidal fracture of the broken grains.

Augite is frequently, but not always, present. When recognisable, its most common form is that of minute globules, like those of the basalts, but of still smaller dimensions, enclosed in the felspars and in the clear ground-mass. Larger irregularly defined fragments, of a pale yellow tint in thick sections, which polarise like the augite globules, are probably also augite.

At the base of the lavas of the Garlton Hills certain rocks occur which present the same peculiar anisotropic ground-mass, but in much smaller quantity. The triclinic felspars are numerous, fresh, and well striated. Augite abounds in large crystals, as well as in smaller globular forms. Magnetite or titaniferous iron appears, but has commonly suffered oxidation. Pseudomorphs of serpentine and black ferruginous opaque matter replacing olivine (?) likewise occur. These rocks evidently form a connecting group between the anamesites and porphyrites.

The most characteristic Carboniferous porphyrites in the Basin of the Firth of Forth are those of East Lothian. They have been laid open in numerous quarries, as well as natural sections, on the Garlton Hills. The Calton Hill and Arthur Seat porphyrites are much decayed, but still show the characteristic ground-mass. The Campsie Fells contain many varieties of porphyrite, but these lie chiefly beyond the region embraced by the present Memoir.

In the progress of alteration the porphyrites undergo some characteristic changes. Their felspar suffers the usual kaolinisation. Their ferruginous constituent is oxidised into hæmatite, but more usually limonite, and they consequently weather into reddish-brown and yellow clays.

C. Felspar (Orthoclase) Rocks.

The Felsites. (Plate XII. fig. 9.)

Very few rocks of this class are included among the Carboniferous volcanic masses of the Basin of the Firth of Forth. Some examples occur among the necks of the Campsie Fells, and in the western neck on the shore at Largo.

1. *General External Characters and Modes of Occurrence.*—Under the term felsites, I group certain rocks varying in colour from a pale grey through shades of yellow to a deep red, usually compact in texture; in fresh fracture sometimes quite flinty, but mostly decayed, and presenting a more or less kaolinised

granular aspect; seldom porphyritic, but generally containing distinct blebs of quartz readily perceptible by the naked eye. They are all intrusive masses, and are confined to the necks or their vicinity. They occur as veins or dykes, sometimes in large neck-like masses.

2. *Microscopic Characters.*—Under the microscope these rocks show a characteristic finely granular felsitic ground-mass, through which are scattered grains or irregular pieces of quartz and crystals of orthoclase (see Plate XII. fig. 9). One of the most interesting varieties is that already referred to as occurring in veins, together with basalts, in the vent on the shore to the west of Largo. It is exceedingly flinty in texture, and looks so like altered shale that I at first regarded it as such. Its extreme hardness causes it to stand out prominently on the beach, where its enduring surface acquires in places a kind of polish from the friction of sand particles across it. Seen with a low power under the microscope, it shows a curious reticulated structure, which, in some respects resembling the normal structure of perlite, is marked by numerous narrow bands running through the rock and often intersecting each other. These bands differ from the rest of the ground-mass in being clearer and less thickly granular. In the interspaces between them the ground-mass thickens into cloudy patches with traces of a fluid structure of the perlitic kind. The orthoclase crystals and quartz, however, are found indiscriminately in the bands and in the interspaces or crossing from the one to the other. The orthoclase occurs in Carlsbad twins, averaging from $\frac{1}{50}$ to $\frac{1}{100}$ of an inch in length. The quartz is not definitely crystallised, but has taken the form of rounded blebs, sometimes with the drop-like form so often to be noticed in felsites. Its granules are distinctly visible to the naked eye, and are crowded thickly through the rock. They abound in cavities.

An interesting feature in this rock is its occurrence in one of the necks of the East of Fife where, with this exception, basalt is the only form of lava now to be seen. Throughout the great plateau of Lower Carboniferous porphyrites, extending from the Campsie Fells into Ayrshire, large bosses as well as veins of a yellow quartz-felsite are not uncommon. Yet no rock of this kind seem ever to have been erupted to the surface. Again, in the Lower Old Red Sandstones, while the outflows of lavas are thoroughly basic porphyrites, large intrusions of siliceous felsites have taken place at and round the necks, but never at the surface. At the Pentland Hills, however, during Lower Old Red Sandstone times, great showers of felsitic tuff were ejected. It would appear that, even at volcanoes giving out basic lavas and tuff, there has frequently been an uprise of extremely acid lavas in and around the vents.

II. The Fragmental Rocks or Tuffs.

(Plate XII. fig. 10.)

From the nature of their origin the fragmental volcanic products cannot, like the crystalline rocks, be grouped into very definite petrographical subdivisions. They are not chemical mixtures, but mere mechanical aggregates, liable to constant variation in the characters and proportions of their constituents. Thus on the large scale we may encounter one of these masses presenting the greatest contrast in the composition even of two adjacent portions; and even when examined with the microscope, similar extreme diversity and variety may be traced.

1. *General External Characters and Modes of Occurrence.*—In the first place, it is to be observed that the fragmental rocks have two distinct modes of occurrence, in each of which they present special petrographical characters. They occur (*a*) filling up volcanic vents, and (*b*) interstratified with bedded lavas or with strata of an ordinary sedimentary kind.

(*a*) In Volcanic Vents.—By far the coarsest and most tumultuously assorted varieties occur in this position. Large subangular or somewhat rounded blocks of sandstone, limestone, or other stratified rock, according to the nature of the surrounding strata, are commingled with abundant blocks of dolerite, basalt, or some other variety of igneous rock in an earthy and gravelly paste of the same materials still further comminuted. These *agglomerates* are for the most part quite unstratified, though sometimes traces of a rude bedding may be discerned among them, the layers standing on end or at high angles in the manner already described (*ante*, p. 463). The agglomerate of Arthur Seat is a well known and excellent example. In some cases the stones are remarkably angular, giving the rock the character of a *breccia*, though this variety is much less frequent than the preceding. The fragmental detritus in the vents is often a dull, dirty-green gravel, partially cemented in an incoherent paste of the same composition. The small stones of the gravel consist chiefly of varieties of dolerite or basalt, usually much decayed. Larger blocks of the same rocks, as well as of sandstones, limestones, shales, &c., are scattered abundantly through the mass. This is the general character of the tuff filling up the vents in Fife. In districts where the lavas erupted have been porphyrites, the volcanic agglomerates and tuffs consist of the debris of these rocks. Fragments of older tuff may constantly be detected among the materials in the vents. The probable meaning of this fact has been already stated (*ante*, p. 461).

(*b*) In Interstratified Sheets.—The showers of dust, sand, and lapilli ejected from volcanic vents falling upon lakes, rivers, or the sea, sink to the bottom of the water, where they accumulate in layers, more or less mixed with the ordinary sand, mud, or other deposit. In proportion, therefore, to the vigour and length of the eruption and to the proximity of the vent will be the thickness of the layer of tuff and its freedom from extraneous materials. But as we recede from the centre of disturbance we find the volcanic debris to be more and more commingled with ordinary sediment until at last it comes to be no longer traceable in the usual sand or silt of the district. Hence, in dealing with the bedded tuffs of the Carboniferous system in the region of the Forth we are constantly presented with varying mixtures of fine volcanic debris and ordinary mechanical sediment. The reality and nature of this commingling can best be seen when the non-volcanic material is limestone, as may be instructively observed among the Kirkton Quarries to the east of Bathgate, and on the Fife coast between Pettycur and Kirkcaldy. (See *ante*, p. 482.)

The bedded tuffs vary according to the nature of the lavas with which they are associated. In the porphyrite districts they are dull red or greenish rocks, made up of fine porphyrite debris, mixed with ordinary sand and clay. In the doleritic and basaltic region they are almost invariably of a characteristic blackish-green to sage-green tint, rarely dull yellow or red; and are well stratified, the layers being marked off by lines of lapilli, consisting of greenish decayed varieties of basalt rocks. Their layers vary from mere laminæ, scarcely thicker than writing-paper, up to thick beds piled over each other to a depth of several hundred feet. Organic remains are frequently to be met with in these tuffs. Thus at the east quarry, Kirkton, we may observe well-preserved fronds of *Sphenopteris* and *Pecopteris*, with stems of *Lepidodendron* and *Calamites*; at the west quarry, *Productus longispinus*, crinoid stems, and other marine organisms; at St Anthony's Chapel, Arthur Seat, scales of *Rhizodus*, and other fish remains.

2. *Microscopic Characters.*—The fragmental rocks do not yield such satisfactory results as the crystalline masses to investigation with the microscope. In thin slices, with a low magnifying power, they are seen to present the same twofold composition as on the large scale to the naked eye, viz., enclosing paste and enclosed fragments.

a. The Paste.—I have never yet succeeded in obtaining any definite structure in the matrix of the tuffs. It is a dull, finely granular amorphous substance, which under a high power is resolvable into shapeless grains and shreds, often greenish, sometimes colourless, and sometimes black and opaque. There can be no doubt that these particles are merely the more thoroughly comminuted debris of the same materials as constitute the distinct lapilli. In no case have I found any microlites such as are met with in some modern volcanic tuffs and ashes. If any such ever existed, they have disappeared in the general oxidation and alteration of the matrix of the rock. The tuffs, being commonly porous incoherent masses, have suffered more from the influence of percolating water than the solid basalts. Probably we never see any of them now in their original condition; so that the diffused red, brown, and green matter of their base may represent microlites and crystals of some of the constituent minerals of the lavas.

Where the tuffs occur as beds or laminæ, interstratified with sedimentary rocks, the paste necessarily becomes mixed with the sand, mud, or limestone which may have been gathering in the floor over which the volcanic eruptions took place. Many good specimens showing this intermixture under the microscope may be gathered from the Bathgate and Pettycur localities already referred to.

b. The Lapilli.—These consist chiefly of rounded or subangular fragments of the lavas of the district in which the tuff lies. In Fife and the Lothians among the districts of basalt and dolerite, fragments of these rocks may be detected abundantly in the tuffs. Many of them do not differ in any respect from the substance of the solid rock as we see it now in sheets or in dykes at the surface. They seem to have been derived from the breaking up of already consolidated lava. This, so far as I have been able to observe, appears to be true also of the whole of the lapilli generally. It is rare to meet with one which has its cells drawn out round its circumference in such a manner as to point to its having been ejected from a molten mass and having acquired its globular form from rapid gyration in the air during its ascent. On the other hand, every section of tuff will furnish examples of cellular lapilli, in which the cells have been cut across by the external surfaces of the fragments. These lapilli are merely portions of vesicular or pumiceous lava, and may have been ejected by explosions that disrupted the hardened frothy crust of a rock, the lower portions of which were still molten and in ebullition underneath. So extremely cellular are many of the lapilli, that where they fell into water they must have floated for some time before becoming water-logged. The vesicles are filled with calcite, delessite, or some other product of decomposition.

One of the most generally diffused constituents of the tuff seems to be peculiar to them. In its present condition it is a serpentine or serpentinous substance, varying in colour from a bright grass-green or celadon-green to pale or honey-yellow, transparent and structureless in thin slices, looking at first like a green glass (see Plate XII. fig. 10). It is almost invariably cellular, sometimes so extremely so that the vesicles form three-fourths of the mass. The cavities are sometimes perfectly circular, and vary from less than $\frac{1}{1000}$ to more than $\frac{1}{100}$ of an inch in diameter. More usually they are elongated, and occasionally have been drawn out to such an extent that they appear as exceedingly thin parallel lines, giving the substance a laminated aspect. In some rare instances the elongation has taken place round the external parts of the lapilli, the inner cells remaining circular. But in almost all cases the vesicles have been broken across by the external surfaces of the lapilli. They appear usually empty in the preparations; but calcite occasionally remains in them

Besides the abundant cells, this substance frequently contains prisms of a triclinic felspar, and sometimes slender needles, which may be apatite. I have also observed round and subangular granules of quartz, containing abundant liquid cavities. This quartz is probably an accidental constituent caught up in the original melted rock, and not properly belonging to its composition. Scattered rod-like and granular black opaque microlites are sometimes observable. Very minute black grains may likewise be noticed, more particularly round the circumference of the cells.*

Viewed with ordinary light this green or yellowish transparent glass-like base of the lapilli at once suggests Palagonite. Between crossed Nicol prisms it is resolved into the pale bluish grey or neutral-tinted finely fibrous appearance, with occasional bright chromatic polarisation so characteristic of serpentine.

There can be no doubt that this serpentine or serpentinous substance must have been originally a glass, in the most thoroughly melted condition, and that it was kept in brisk ebullition by the passage of vapour through it. It has no counterpart among the lavas erupted at the surface. The nearest analogy is to be found in the Blackburn "pikrite" already described; but there is nothing in that rock like the minutely and abundantly cellular structure of the lapilli in the tuffs. These fragments occur chiefly in the tuff of vents; they abound in the necks of the Fife coast, sometimes to such an extent as nearly to constitute the entire mass of the tuff, as at Kilmundy Hill, near Burntisland. They may be observed in the later agglomerates of Arthur Seat, at St Magdalene's, Linlithgow, &c. They occur less frequently in the interstratified sheets of tuff, as among some of the beds at Pettycur and Kinghorn. I regard them as having been derived from the explosion of a rock which contained little felspar, but probably consisted mainly of olivine and augite, and which remained for a long while simmering, as it were, at the bottom of some of the volcanic vents. I have pointed out, in the case of the remarkable Blackburn rock, that a segregation of its materials had taken place, the heavy olivine remaining chiefly below. Something of the same kind may be supposed to have occurred in the volcanic funnels. After long fusion the lighter minerals, notably the felspar, may have come chiefly to the top, whence they might be discharged at successive volcanic eructations. Eventually the lower and

* Since the above description was written, I have had an opportunity of examining the artificially fused products of some of the basalts and dolerites from the neighbourhood of Edinburgh (*ante*, p. 498, note). The resemblance of this altered serpentinous cellular substance, so abundant in some of the volcanic vents, to the glass obtained by fusing such a basalt as that of the Lion's Haunch, is so remarkable as at once to suggest an original similarity of condition. This glass, artificially obtained from some rocks like that of the Lion's Haunch, where the felspar resists fusion, must consist mainly of olivine and augite with diffused magnetic iron, and, as I have already said, it contains tufted microlites not unlike those of the tuff-lapilli.

heaver portions would be similarly ejected before the next great explosion, bringing up fresh streams of lava from below.

One of the most common constituents of the tuffs is quartz, in the form of rounded and subangular grains. When I first observed these enclosures I naturally supposed them to be merely the grains of sand that might have been in suspension in the water or moving along the floor over which the volcanic detritus settled. This may be partly their origin. But I am now convinced that they were directly ejected from the volcanic orifices in great quantity, for I find them in greater or less abundance in the tuff of all the vents. They are singularly uniform in character, consisting of water-clear quartz, free of enclosures, except abundant liquid-cavities, which may often be observed in lines across the diameter of the quartz-grain. These particles of quartz are manifestly derived from the destruction of some highly silicated rock. I have tried to account for their presence, on the suppôsition that they are due to the thorough trituration of quartzose sandstone. But this hardly accounts for their complete isolation from each other, for the want of any crust such as so frequently surrounds the quartz-grains of sandstones, and for the absence of fragments of sandstones which had escaped disintegration, and of pieces of shale and such other stratified rocks as could hardly fail to be present. As I have just mentioned, these separate quartz-grains are sometimes found within the solid substance of the serpentine lapilli. They must have been enclosed in the original olivine-rock while it was still molten.

Among the tuffs must be included some rocks, to which the name of volcanic mudstone may be applied. They are dull, dirty-green rocks, with a matrix varying from a fine impalpable hardened mud to a finely granular tuff, and containing lapilli and frequently fragments of shale, sandstone, limestone, &c. They occur at the margin of vents, wrapping round the projecting portions of the walls, and showing by wavy lines of flow distinct traces of having been in a pasty condition. To the east of Elie they rise through the tuff of the vents as dykes, which from their hardness rival basalt in their prominence above the surrounding softer tuff. One of these rocks is of an exceedingly close-grained texture, scarcely at first to be distinguished from a dull basalt, for which it has been mistaken. It has been already referred to as containing abundant pieces of a black cleavable hornblende and worn twin crystals of orthoclase. When the included fragments are carefully removed, their smooth surfaces leave a clean, sharp cast on the fine-grained mudstone. Examined with the microscope, the rock is found to consist of a dark-brown or greenish amorphous granular matrix crowded with small granules of quartz, with numerous minute lapilli of basalt rocks. It contains also occasional fragments of hornblende and plates of biotite.

EXPLANATION OF PLATES.

PLATE IX. Map of the Volcanic Districts in the Basin of the Firth of Forth.

PLATE X. Vertical Section of the Lower Part of the Carboniferous System in the Basin of the Firth of Forth, showing the succession of Volcanic Eruptions.

PLATE XI. Microscopic Structure of the Volcanic Rocks of the Basin of the Firth of Forth.

Fig. 1. Diabase, Crossall Hill, Linlithgowshire.—The felspar is chiefly orthoclase in Carlsbad twins, with the "herring-bone structure" described on p. 488. The augite occurs in large crystals and aggregations of crystals of a delicate claret colour. Some large crystals and a portion of a remarkable compound crystal of titaniferous iron are shown. The long white rod and the numerous colourless hexagonal sections are apatite. A few brown fibrous plates of biotite appear. (20 diameters.) See p. 487 *et seq.*

Fig. 2. Diabase, Corstorphine Hill, Edinburgh.—The augite is conspicuous in the centre of the field, surrounded by a turbid milky felspar. The opaque titaniferous iron appears to shade off into a whitish dull translucent substance (leucoxene). Patches of bright green decomposition products, sometimes with tufted fibrous structure, fill up some of the interstices. (20 diameters.) See p. 487 *et seq.*

Fig. 3. Dolerite, Dalmahoy Hill, Edinburgh.—An intrusive rock, showing abundant large clear prisms of a triclinic felspar, numerous large but rather ill-defined crystals of pale brownish pink augite, which has sometimes enclosed the felspar prisms. The titaniferous iron occurs in smaller forms than in the coarser diabases. Between the various minerals a considerable proportion of a ground-mass is interposed, which is in large measure devitrified by the appearance of microlites, and which now encloses a good deal of green decomposition-products in tufts, threads, and streaks. It is likewise traversed by clear needles of apatite, and marked by brown spots of limonitic discoloration. (20 diameters.) See p. 493.

Fig. 4. Anamesite, Craiglockhart Hill, Edinburgh.—This section is placed beside fig. 3 to show the distinction between intrusive and bedded rocks of the dolerite type. It shows a crystalline admixture of clear labradorite prisms, with abundant granular augite, through which are scattered a few large, well-formed crystals of the latter mineral, with crystals of olivine, usually serpentinised. One large well-defined olivine, with its green transverse decomposed portions and the central still comparatively fresh kernels, forms a prominent feature in the drawing. The iron is in very minute forms, and appears to be chiefly magnetite. (20 diameters.) See p. 501 *et seq.*

Fig. 5. Basalt, Kirkton East Quarry, Bathgate.—This section represents the structure of a typical interbedded basalt of the district. The rock evidently consists of an intimate mixture of minute prisms of labradorite and granular augite, between which clear interstices appear filled with a glassy ground-mass. A few well-defined usually compound crystals of augite are interspersed, but are not so abundant or conspicuous as the olivines, which are almost invariably converted into green serpentine. Octohedra of magnetite are tolerably uniformly dispersed through the rock. The minutely granular condition of the augite in this rock and in fig. 4 may be contrasted with that of the intrusive rocks Nos. 1, 2, and 3. (20 diameters.) See p. 501 *et seq.*

Fig. 6. Pikrite, Blackburn, Bathgate.—This rock consists mainly of serpentine of very varied texture and colour, containing numerous tolerably well-marked forms of the original olivine, and occasionally reticulated portions in which the distinct polarisation of the latter mineral may still be detected. The augite occurs in large admirably fresh well-defined crystals of a fine claret colour in thin slices. It often encloses crystals of olivine. A few fragments of magnetite or titaniferous iron are shown with here and there traces of their having been oxidised and hydrated into the brown hydrous peroxide of iron. (20 diameters.) See p. 504.

PLATE XII.

Fig. 7. Porphyrite, Pencraig Quarry, Garlton Hills.—A rock, consisting mainly of triclinic felspar, in small ill-defined prisms, with abundant grains, shreds, and crystals of magnetite and occasional augite. Traces of the oxidation and hydration of the iron are seen in the brown spots. (20 diameters.) See p. 508.

Fig. 8. Same as fig. 7, seen between crossed Nicol prisms. The ground-mass interposed between the felspar crystals now appears clouded, being partly quite dark and partly admitting a milky blue light. (20 diameters.)

Fig. 9. Felsite, Volcanic Neck, Shore at Largo, Fife.—A finely granular felsitic ground-mass, with a kind of perlitic structure. In certain portions of the rock between the wavy lines of closer aggregation in the ground-mass, clear crystals of samidine and granules of quartz, with fluid cavities, are enclosed. (20 diameters.) See p. 510.

Fig. 10. Tuff, Kilmundy Hill, Burntisland.—An aggregate of irregular fragments of different lavas. The largest of these here shown consists of a bright green serpentinous substance, exceedingly cellular, and containing occasional plagioclase crystals and microlites (see p. 513). Between the lapilli much brown opaque decomposed matter is diffused.

Fig. 11. Veins of Dolerite traversing altered Shale, Salisbury Crags, Edinburgh.—The dolerite is exceedingly close-grained, becoming here and there, especially along the edges, quite black and opaque. At the lower portion of the field it is seen to be full of microlites of titaniferous iron or magnetite. It encloses numerous perfectly formed prisms of triclinic felspar. The shale consists of a porcellanised base, with clear round granules of quartz. See p. 497.

Fig. 12. Dolerite from edge of sheet near contact with sandstone, Gartness, Airdrie.—The large prisms of triclinic felspar and patches of titaniferous iron are the most conspicuous features. No augite appears, its place being probably taken by some of the abundantly diffused green decomposition products. The remarkable forms originally assumed by the iron, and preserved in those parts of rock which have been rapidly congealed, are shown in this drawing. See p. 496 *et seq.*

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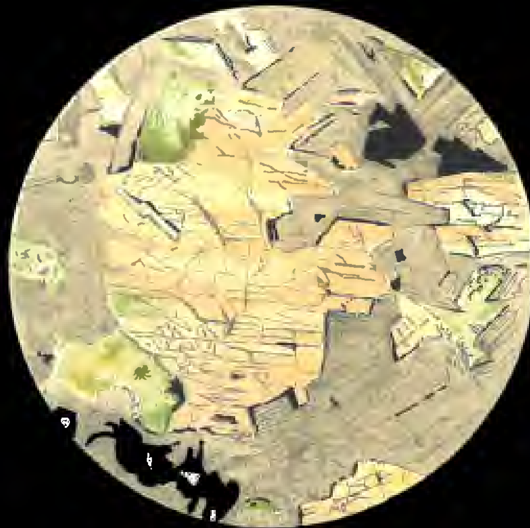

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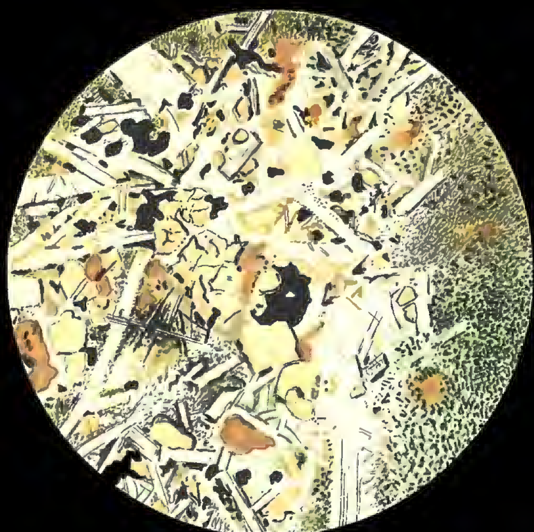

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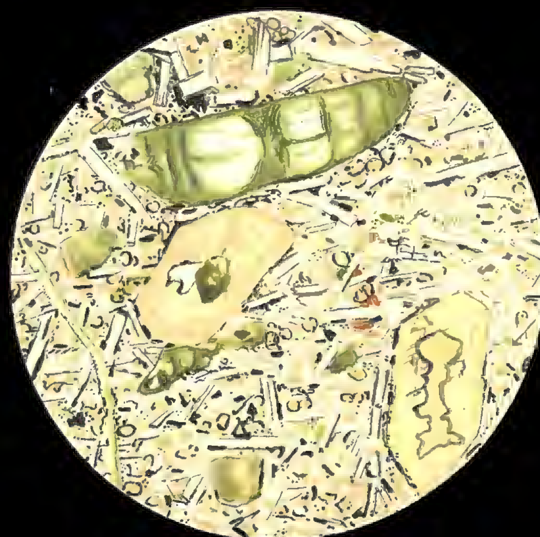

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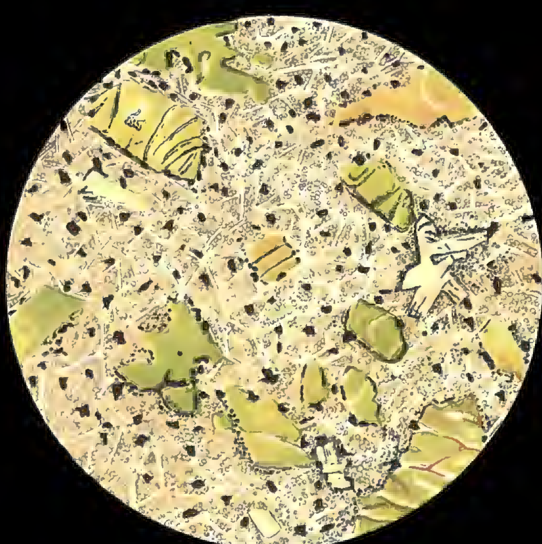

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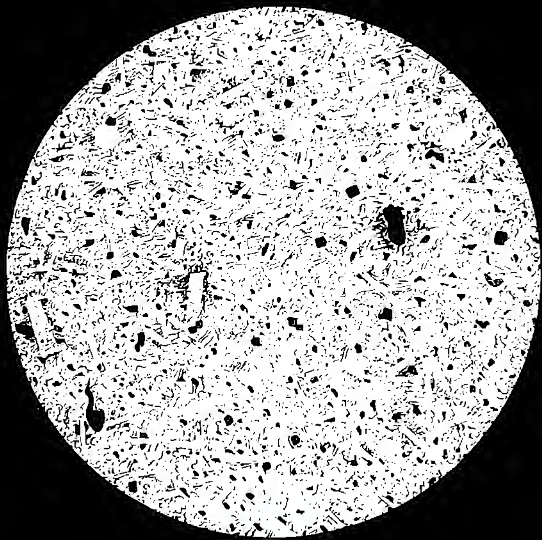

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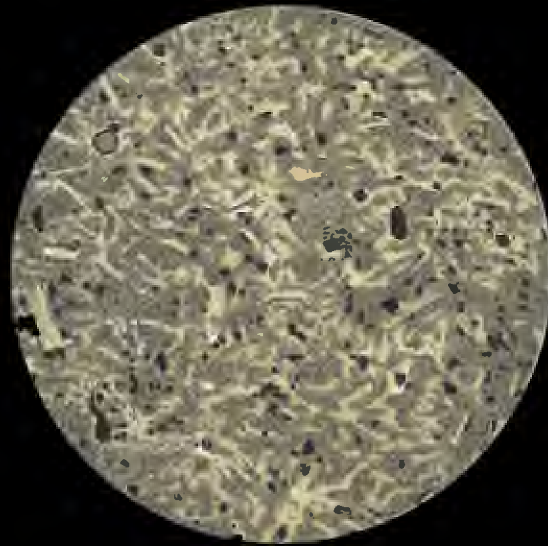

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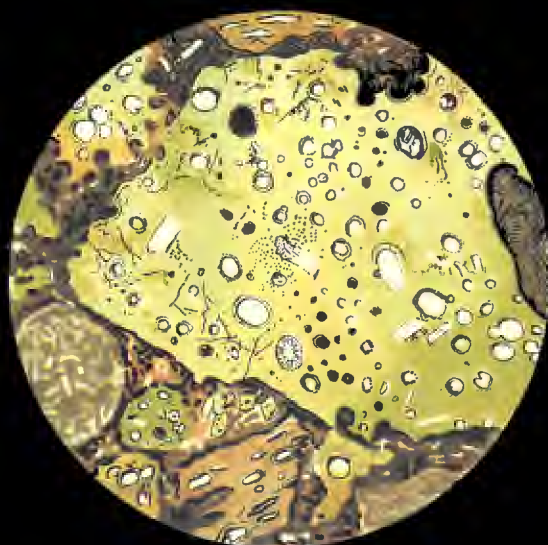

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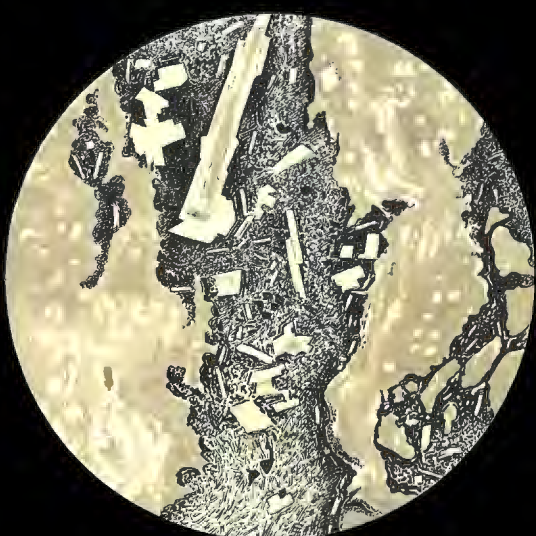
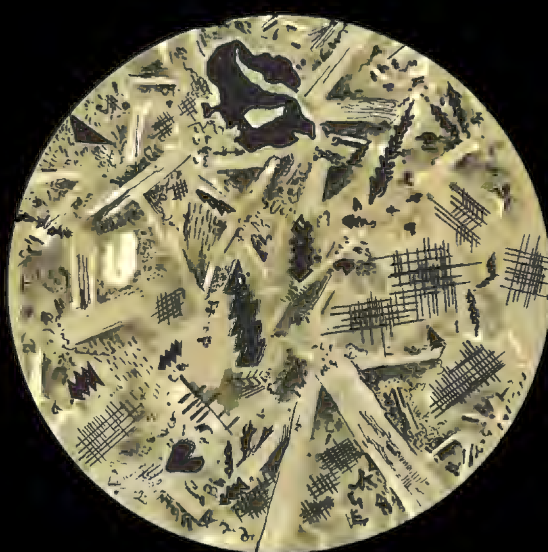


11



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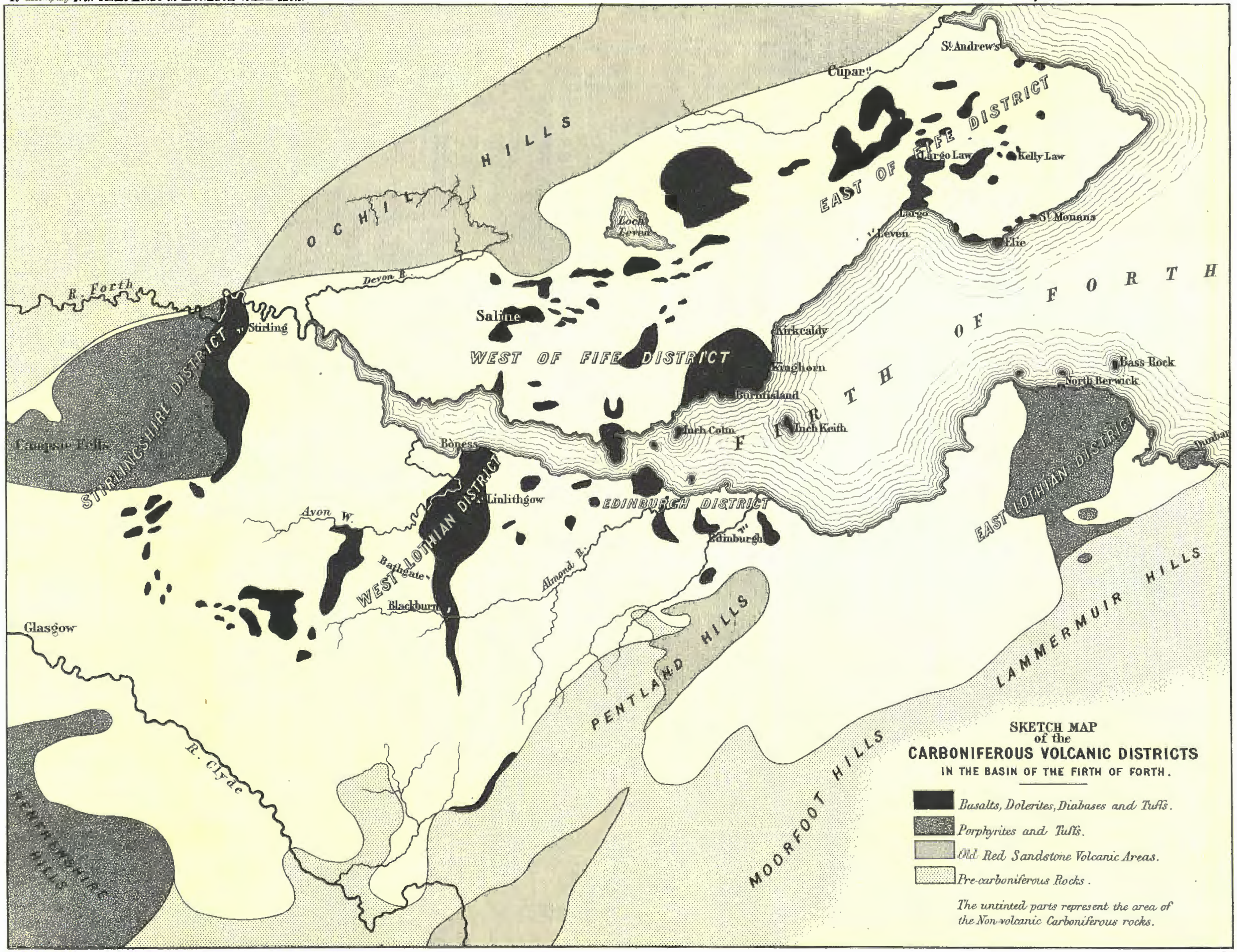
Chromo-Lithog. by W & A K Johnston Edinburgh & London



Lithog. by W. & A. K. Johnston Edinburgh

SUCCESSION OF VOLCANIC ROCKS
IN THE CARBONIFEROUS SYSTEM OF THE BASIN OF THE FORTH.