The late Palaeozoic quartz-dolerites and tholeiites of Scotland.

(With Plate V.)

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CONTENTS.

1. INTRODUCTION AND LITERATURE.

TOWARDS the close of the Carboniferous period in Britain, igneous activity, which had been prominent from time to time throughout the system, broke out afresh in a new form affecting a large area of the country between the Moray Firth and the River Tees. This activity was entirely hypabyssal in character, the intrusions consisting of basic dikes and sills belonging without exception to the tholeiite magma-type of Dr. W. Q. Kennedy [1] and W. Wahl. Those in the north of England include the famous Whin Sill and have been studied in great detail, particularly by Professor A. Holmes [2] and by Dr. J. A. Smythe.[3] The same cannot be said of their Scottish representatives. They possess, indeed, an abundant literature and several excellent publications deal with the intrusions of limited areas, but there is no connected account of them as a whole. Many districts, in fact, appear to have escaped investigation almost completely. The present paper is an attempt to fill some of

[1] W. Q. Kennedy, Trends of differentiation in basaltic magmas. Amer. Journ. Sci., 1933, ser. 5, vol. 25, pp. 240–242.

[2] A. Holmes and H. F. Harwood, The age and composition of the Whin Sill and related dikes of the north of England. Min. Mag., 1928, vol. 21, pp. 493–542.

[3] J. A. Smythe, A chemical study of the Whin Sill. Trans. Nat. Hist. Soc. of Northumberland, Durham, and Newcastle-upon-Tyne, 1930, vol. 7, pp. 16–150.

the major gaps in the literature and to give, with the aid of new chemical and micrometric data, a more comprehensive account of the whole suite than has hitherto been published. No claim to completeness is made, for a great deal of work still remains to be carried out on these intrusions.

Only the more important references in the literature are given in the list below, in which redundance is avoided as far as possible. Attention may also be directed, however, to the Economic Memoirs of the Geological Survey of Scotland, in particular to those of the Fifeshire, Kinross-shire, and Stirlingshire coal-fields. Numerous brief references to the field relations of the intrusions occur throughout the text of these publications.

It is unnecessary to summarize this long list of papers. The best general petrological accounts are those of Professor J. D. Falconer (15), Dr. G. W. Tyrrell (21), and Sir John Flett (22, pp. 301–311), while an admirable summary of the field evidence relating to the age of the intrusions is given by Professor E. B. Bailey (30, pp. 150–151). The two most important advances in the study of the suite are the recognition by J. J. H. Teall (4) of primary quartz as micropegmatite in the Lothian sills and their resemblance to the Whin Sill, and the discovery by C. T. Clough (8) that the E.–W. dikes are cut by members of the NW. Tertiary swarms and may therefore be of Palaeozoic age.

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37. 1932 S. BUCHAN, On some dykes in E. Aberdeenshire. Trans. Geol. Soc. Edinburgh, vol. 12, pp. 323–328.
38. 1934 F. WALKER, A preliminary account of the quartz-dolerite dykes of Perthshire. Trans. Perth. Soc. Nat. Sci., vol. 9, part 4, pp. 1–9.

2. FIELD CHARACTERS.

Distribution.—A sketch-map (text-fig. 1) showing, as far as possible, all the recorded dikes together with the areas in which the associated sills occur is given on p. 135, and it will be seen at once that the distribution of the intrusions presents certain well-marked features. The sills are confined almost entirely to strata of Carboniferous age, the one possible exception being the sill of Corriefodly in Strathmore (33, p. 87) where the country-rock is of Lower Old Red Sandstone age. They are prominent in the middle and eastern portions of the Midland Valley but are completely absent from the Carboniferous strata west of Glasgow.

The dikes, on the other hand, are found in all formations up to and including the Coal Measures. Apart from sporadic outlying occurrences they appear to belong to two great swarms—one trending E.–W. across the country from Dunbar to Jura, and the other trending ENE. from Stonehaven to the head of Loch Fyne. Many of the separate outcrops mapped in Strathmore, the NE. Grampians, and Aberdeenshire (37, p. 323) might be connected up to form continuous dikes with some probability, but the country in this region is so thickly covered by drift that exposures are very poor. The northern swarm seems to find its maximum development in the district between Callander and Loch Tay and tends to spread out slightly both ENE. and WSW. of this focus. In the case of the southern swarm no sign of spreading is seen either to the E. or W. of the region of maximum development which appears to be in the neighbourhood of Falkirk. A curious feature is the relative absence of dikes from southern Fifeshire—a district where sills are exceedingly prominent. The significance of the distribution of both dikes and sills will be withheld until a later stage.

Form and Topography.—In most districts both dikes and sills tend to stand out as prominent features of the landscape owing to their superior hardness, and it is only in regions where the country-rock is

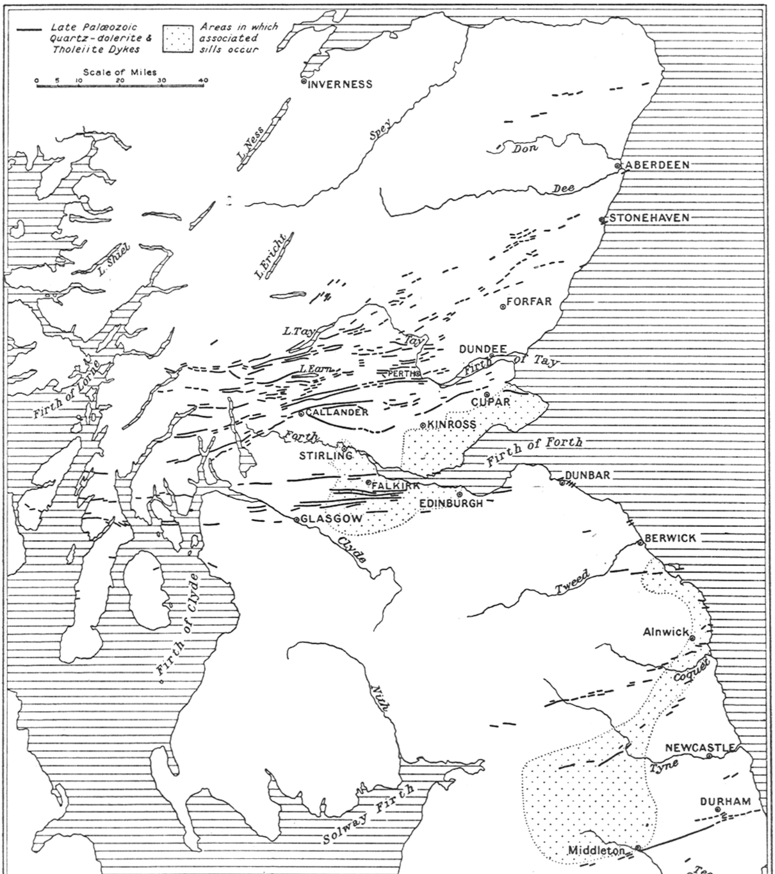

FIG. 1. Sketch-map showing distribution of quartz-dolerite and tholeiite dikes and associated sills.

resistant to weathering and thickly covered by drift (e.g. Strathmore) that exposures are poor. The sills usually show well-marked escarpments along which more or less rounded rectangular joint blocks project from the rich, warm-brown soil so characteristic of the weathering of these intrusions. Spheroidal weathering is frequently visible, but the columnar jointing often seen in the Carboniferous olivine-dolerite and teschenite sills is very rare. Some of the sills reach a considerable thickness, as, for instance, the main sill of the Kilsyth-Croy district, which has been proved by a diamond bore to be over 300 feet thick (30, p. 153). Another feature which distinguishes them from the olivine-dolerites and teschenites is their tendency to change their horizon abruptly. This renders estimates of their area a difficult matter.

The dikes usually stand out as conspicuous ridges, often wooded, and sometimes with wall-like sides exhibiting basaltic selvages. A very common breadth is about 60 feet, but numerous examples are known over 100 feet across, one between Croy and St. Flanan (30, 157) reaching a width of 190 feet. On several of the older one-inch maps of the Geological Survey breadths of 300 feet or more are shown, but when these localities were visited by the author it was found that in no case did the dike in question measure much more than 100 feet across. Some of the dikes rival in length the great Tertiary examples which cross the Southern Uplands, one actually stretching from Newton Hill in NE. Fife to the head of Loch Fyne—a distance of over 80 miles. The majority of them have risen vertically upwards.

Relation of dikes to sills.—As in the north of England, the dikes and sills of the suite are petrologically identical, but the relationship between the two types of intrusions can be made out more easily in Scotland. It has been suggested by B. N. Peach, upon convincing field evidence, that the Lenzie-Torphichen dike acted as the feeder of the adjacent sill complex, and this conclusion has been confirmed by the work of C. B. Crampton in the Mollinburn district (30, pp. 149–150). On the other hand, a sill at Ravenscraig in the Bathgate Hills may be definitely shown to cut an E.–W. dike (22, p. 285), while a dike in the Kilsyth-Croy complex has all the appearance of cutting a sill (30, p. 157). Consideration of the evidence seems to indicate that both dikes and sills belong to the same period of intrusion, but that this period was somewhat prolonged—a conclusion confirmed by the tectonic evidence as outlined below.

Tectonics.—Detailed examination of the relevant one-inch maps shows clearly that the suite has a close connexion with the faulting and folding which affected the country at the close of the Carboniferous time. Taking the dikes first it will be noted that those of the southern swarm (occurring in Carboniferous strata) maintain an

E.–W. trend with little variation other than local. They are obviously connected with the great E.–W. normal faults which cross the Midland Valley and are the result of tension from N. to S. At several places between Linlithgow and Glasgow the dikes appear to have risen upwards along the fault fissures. Elsewhere the dikes are found in older rocks and here their trend is determined by the result of competition between movements of the Caledonian and Hercynian age. In each district the dikes follow roughly the direction of the dominant faults. In northern Perthshire the Caledonian trend is dominant, but the members of the northern swarm have an ENE. trend along Strathmore and the Highland Border swinging round to E.–W. in western Perthshire and Argyllshire. The Hercynian movements seem also to have prevailed in the western portion of the southern swarm as well as in northern Aberdeenshire. On the maps of Highland areas a great many faults, whatever their trend, are shown as cutting the dikes without shifting the outcrop. Since most of the dikes are vertical, this may often be the case provided the dislocation causes no horizontal displacement, but it is exceedingly doubtful whether this relationship holds good as frequently as recorded on the maps. It is, in fact, probable that many of the dikes are actually later than the faults, as in the Midland Valley. Another feature of the Scottish dikes is the apparent absence of the echelon arrangement so prominent in their north of England neighbours and considered by Professor Holmes (loc. cit., pp. 514–515) to be the result of differential rock flowage which he compares to the conditions obtaining in valley glaciers where a series of marginal crevasses in echelon formation is a common phenomenon. Some of the Strathmore outcrops may possibly represent an echelon system, but there is no evidence of strong differential rock flowage akin to that in Northumberland; moreover, the exposures are largely concealed by drift.

The case of the sills is slightly more complex. In the Kilsyth-Croy area they appear to traverse powerful E.–W. faults without being thrown by them, or to change their horizon to an extent quite inconsistent with the measured throw of the dislocation. Thus in some cases they seem to be later than the faulting (30, pp. 154–155). There are, however, several examples in this district, besides numerous others in Fife, Stirlingshire, and the Lothians, of sills being thrown by E.–W. faults. When the relationship of the sills to the folding is considered the same contradictory evidence is encountered in the Kilsyth-Croy district (30, pp. 155–156). At Barr Hill the sills seem to be later than the folding, while elsewhere they are definitely earlier. In the other districts they seem almost certainly to be earlier than the folding.

One may conclude therefore that both dikes and sills were more or less contemporaneous with the Permo-Carboniferous folding and faulting, but that the period of intrusion was probably somewhat prolonged.

Age.—If it be admitted that all the dikes and sills of the suite belong to the one period of intrusion, we can then fix their age almost beyond dispute. Tectonic considerations, as shown above, point to a Permo-Carboniferous age, but there is other evidence bearing on the point. Some of this is well summarized in the Glasgow Memoir (30, pp. 150–151).

The most important additional piece of evidence is the discovery by Professor Holmes in 1925 and confirmed by Dr. L. Hawkes of a pebble of undoubted Whin Sill type in the Permian Upper Brockram of the Eden Valley (loc. cit., pp. 532–534). An upper limit has thus been put to the age of the suite. The presence of fluorite in the Yellow Sands below the Magnesian Limestone of Yorkshire and its absence from the Coal Measures [1] is also taken to indicate that the mineralization which affected the Whin Sill was of Permo-Carboniferous age. Now in Scotland members of both the dike and sill phases petrographically identical with the Whin Sill are seen in many places to cut Coal Measures and a Permo-Carboniferous age may thus be assumed for the whole suite.

The evidence against a Permo-Carboniferous age is not strong. Mrs. I. F. Wallace [2] detected blocks of hypersthene-bearing quartz-dolerite in the ash vents of east Fife and the work of Mr. D. Balsillie has shown that some, at least, of these vents are of Lower Carboniferous age. Mr. Balsillie has pointed out that quartz-dolerites of Old Red Sandstone age are found among the sills of Angus in the neighbourhood of Dundee, and might also occur in the Lower Carboniferous intrusions; but the Angus examples are petrographically quite distinct from the blocks in the vents which are of identical

[1] The Permian strata of Scotland unfortunately lie outside the path of the two dike swarms.

[2] I. F. Wallace, Notes on the petrology of the agglomerates and hypabyssal intrusions between Largo and St. Monans. Trans. Geol. Soc. Edinburgh, 1916, vol. 10, pp. 357, 359, and 360.

type to sills of our suite cutting Coal Measures. Furthermore, an E.–W. quartz-dolerite dike at Kingask is seen to traverse an ash vent (11, p. 198). It seems probable, therefore, not that the suite is of other than Permo-Carboniferous age, but rather that the volcanic activity of east Fife persisted throughout the Carboniferous System—a conclusion supported by the occurrence of vents piercing the Millstone Grit and Coal Measures of the Leven coal basin.

Multiple injections.—The segregation of acid mesostasis into pink or grey contemporaneous veins and patches has long been known as one of the most striking features of the quartz-dolerite members of the suite; but the frequent occurrence of basaltic veins of similar composition to the normal rock, but of distinctly later age, has been less widely recognized. This basaltic phase may become quite important, as at Binny Craig in West Lothian (33), but is usually confined to veins a few inches thick showing sharp junctions (which may or may not be chilled) against the normal rock. The best examples are seen in the quartz-dolerite sill at Greenside Farm, Fife; the quartz-dolerite dike at Haggs Farm below Dalmahoy Hill, Midlothian; in the tholeiite dike crossing the river at Tannadice in Angus; and in other tholeiite dikes at Tullymet (two miles east of Ballinluig, Perthshire) and Wolfhill (three miles east of Stanley Station, Perthshire). At the four last localities the basaltic veins show well-marked chilling against the normal rock and the dikes may consequently be considered as multiple.

3. Mineralogy.

Like all other rocks of tholeiitic magma-type the intrusions of the suite are of comparatively simple mineral composition. Plagioclase felspar, pyroxene, and iron-ore are in all cases amongst the dominant minerals, but any of the minor constituents such as micropegmatite, glass, hornblende, biotite, olivine, and chlorophaeite may become important locally. A description of the major constituents follows together with notes on some of the minor.

Felspars.—Plagioclase is always the most abundant constituent present and is remarkably uniform in its characters throughout the suite. It forms long columnar crystals which in the normal rock show a ratio of length to breadth about 4. The crystals have well-defined edges in the prism zone but irregular terminations. Carlsbad and albite twinning are exceedingly common and pericline twinning rare. There are, however, numerous rectangular sections parallel to (010) which show no twinning.

The bulk of the felspar seems to be labradorite with a composition in the neighbourhood of $Ab_{50} An_{50}$, β being about 1·558 while the maximum symmetrical extinction given by sections normal to the albite lamellae is 27°. Zoning is always present, however, and the margins of the crystals often consist of a thin layer of oligoclase ($Ab_{80} An_{20}$). In several rocks, notably those of the dike in Corsiehill quarry near Perth and of the Lornty dike one mile north of Blairgowrie, distinctly more basic felspar was recorded with symmetrical extinction-angles up to 32°, β 1·563, and a composition about $Ab_{30} An_{70}$. In the case of the Lornty rock the basic felspar occurs as phenocrysts. No sign was seen in any rock of the anorthite phenocrysts recorded by Holmes (loc. cit., pp. 502–503) as occurring in the Whin Sill and its related dikes.

Besides the plagioclase described above a certain amount of alkali-felspar occurs in the quartz-dolerites. This may be either albite or orthoclase and occurs in the interstices between the plagioclase laths mainly in micrographic intergrowth with quartz. The micropegmatite is often so fine that it can only be distinguished under the highest powers of the microscope, but in other sills, particularly in those of the Denny-Stirling complex, it is relatively coarse. It is, on the whole, more prone to decomposition than the more basic plagioclase.

Pyroxenes.—The pyroxenes of the suite present many features of considerable interest. In the case of the tholeiites only one variety is found in an unaltered state, but in several of the quartz-dolerites three pyroxenes are found.

What may be termed the normal pyroxene of the suite—that is, the only fresh pyroxene of the tholeiites and the most abundant of the quartz-dolerites—is a pale-brown monoclinic variety standing roughly between the clinoenstatite-pigeonite and diopside-hedenbergite series. This pyroxene is of sub-ophitic habit (sub-doleritic of Krokström)[1] and in rocks where other pyroxenes occur it was invariably the last to crystallize, though in examples rich in micropegmatite it is sometimes idiomorphic. It is non-pleochroic and has an extinction-angle ($\gamma:c$) of 42°–44°. The optic axial angle (2V) of this variety was measured in slices from a considerable number of localities

[1] T. Krokström, Ophitic texture and the order of crystallization in basaltic magma. Bull. Geol. Inst. Univ. Upsala, 1933, vol. 24, p. 199.

(both tholeiites and quartz-dolerites) with and without the universal stage. These measurements showed a variation between 45° in the case of the tholeiite from Corsiehill quarry to 52° in quartz-dolerite at Auchterarder Station. 48° was found to be a common value for 2V and it was further noted that there was very little zoning or variation of 2V in individual crystals. The pyroxene of the analysed tholeiite of Kinkell (36, p. 371) with 2V 48° gave the following values for the three refractive indices (measured by oils) α 1·699, β 1·708, γ 1·720. Sir John Flett (22, p. 304) made careful measurements of the value of 2E in the normal pyroxene of the quartz-dolerites of Sheet 32 and found it to vary between 80° and 82½°. These figures were confirmed absolutely by the author's measurements in the case of the rocks of the Ratho and West Craigs sills. In most cases the normal pyroxene is unaltered but when decomposition does take place it usually takes the form of alteration to carbonates from the centre outwards. Both simple and lamellar twinning parallel to (100) are common.

The other monoclinic pyroxene is quite different in appearance and is much rarer, occurring only in a few of the coarser quartz-dolerites, notably that of Ratho. It shows the pleochroism of hypersthene in faint tints, but $\gamma : c$ is 42° and $\gamma - \alpha$ about 0·021. 2V is variable but is distinctly lower than that of the normal variety. Some crystals are almost uniaxial, but values of 20°–30° are more common. The habit too is different, for it occurs as elongated prisms, sometimes showing sahlite striation, rather than sub-ophitic aggregates. It is invariably associated with rhombic pyroxene, which it greatly resembles when examined by ordinary light. This pyroxene is evidently a variety of pigeonite differing considerably in its optical properties from those described by Dr. T. Barth from the Hawaiian Islands.[1] It precedes the diopsidic pyroxene in crystallization, but is later than the rhombic pyroxene in the rare cases where the two are seen in contact. Though not so common as hypersthene it is found fairly commonly in the Edinburgh sills, the Bathgate Hill sills, and in the sill complex stretching from Stirling through Denny to Kilsyth. It has also been detected in dikes in Jura (24, p. 113) and Aberdeenshire (36, p. 326).

Rhombic pyroxene occurs in practically all the coarse quartz-dolerites and is represented by pseudomorphs in serpentine or chlorophaeite in many of the tholeiites. Like the pigeonite it is

[1] T. F. W. Barth, Amer. Journ. Sci., 1931, ser. 5, vol. 21, p. 377 [M.A. 4–508].

more liable to decomposition than the normal pyroxene. The fresh mineral shows pleochroism in pink and green tints of variable intensity. It is optically negative and the values for β and $\gamma - \alpha$ are usually about 1·700 and 0·012 respectively. Always the first of the pyroxenes to crystallize, it occurs as elongated prisms which occasionally attain a considerable length. In some of the tholeiites great difficulty was found in distinguishing pseudomorphs after hypersthene from those after olivine.

Iron-ore.—The chief iron-ore of the quartz-dolerites and tholeiites has long been considered to be a titaniferous magnetite or ilmenite. In support of this view are its decomposition in places to grey leucoxene and its frequent skeletal habit. Writing of the Whin Sill, however, Dr. J. A. Smythe (loc. cit., pp. 63–66) has adduced chemical evidence to show that ferric oxide may function under magmatic conditions as a ferrous ferrite ($FeO.FeO_2$) and may thus join solid solutions with ilmenite ($FeO.TiO_2$). The same may be true of the Scottish rocks, but there is no evidence on this point. However that may be, the skeletal or even reticulate habit of the iron-ore is perfectly developed in some of the tholeiites, particularly in the beautifully fresh examples from the north of Kinkell quarry (36, pp. 371–372).

Another iron-ore of frequent occurrence, particularly in the quartz-dolerites, is pyrite. In most cases it has a scaly habit and appears to be of aqueous and post-magmatic origin, being often concentrated along the contacts and joint-cracks.

Hornblende. In some of the coarser quartz-dolerites, e.g. the rock of Devonshaw quarry in Kinross-shire, cinnamon-brown hornblende occurs in parallel marginal intergrowth with the normal pyroxene. It shows moderate pleochroism in tints from clove-brown to almost colourless. $\gamma : c$ is 12–14°.

Biotite.—Dark red-brown biotite is of sparing occurrence in some quartz-dolerites as small flakes which appear in the main to be the product of reaction between the iron-ore and the magma.

Olivine.—No fresh olivine is found in either the quartz-dolerites or tholeiites of the suite, but pseudomorphs with the characteristic lozenge-shaped outline are frequently seen in the tholeiites and at the margins of some of the quartz-dolerite sills. The alteration product is usually serpentine, but in a few cases appears to be chlorophaeite. As mentioned above, it is often a matter of considerable difficulty to distinguish between pseudomorphs after olivine and hypersthene.

Chlorophaeite. Ever since the detection of chlorophaeite in the tholeiite of Dalmahoy by Drs. R. Campbell and J. W. Lunn,[1] its widespread occurrence in the suite under consideration has become increasingly evident. Not only is it found as a replacement product of olivine or hypersthene in both quartz-dolerites and tholeiites, but it appears to be in some cases a primary mineral of late consolidation, e.g. in the tholeiites of Dalmeny and Kinkell (36). In such instances it would appear that the iron was held up till a late stage and eliminated as chlorophaeite just before the consolidation of the residual glass (F. Walker, 36, p. 376; Campbell and Lunn).[2] A curious tholeiitic rock from an E.–W. dike at Lochearnhead has a groundmass consisting almost entirely of chlorophaeite.

Glass.—Unaltered glass occurs in only two tholeiites—those of Dalmeny and Kinkell (36). It is perfectly clear, of pale brown colour, and is crowded with microlites of plagioclase and pyroxene or lattices of ilmenite. The refractive index in each case is 1·495. In a few other tholeiitic dikes, notably those in the neighbourhood of Cortachy, Angus, and the example on the north face of Newton Hill, near Wormit, Fifeshire, alteration is only incipient and the glass slightly turbid. In the last tholeiite the glass is found lining vesicles which contain centres of quartz and calcite (pl. v, fig. 5). The plagioclase laths round these vesicles have a rough tangential arrangement. More often, however, the glass is completely decomposed to turbid reddish-brown material. It is often difficult to ascertain whether such decomposition products represent altered glass or cryptopegmatite. The fresh glass from the Kinkell tholeiite was isolated and analysed, the results being given below.

4. Petrological Characters and Classification.

With the exception of the coarser quartz-dolerites, all the rocks of the suite present much the same appearance in the hand-specimen. They are medium-grained and dark grey or black in colour when fresh, but assume a greenish tinge when decomposed. A characteristic reddish-brown crust forms on weathered surfaces. In the coarser quartz-dolerites the individual constituents can be made out with the unaided eye. Black, gleaming cleavage surfaces of pyroxene

[1] R. Campbell and J. W. Lunn, Chlorophaeite in the dolerites (tholeiites) of Dalmahoy and Kaimes Hills, Edinburgh. Min. Mag., 1925, vol. 20, pp. 435–440.

[2] R. Campbell and J. W. Lunn, The tholeiites and dolerites of the Dalmahoy syncline. Trans. Roy. Soc. Edinburgh, 1927, vol. 55, pp. 508–509.

are frequently conspicuous and occasionally take on a deceptive resemblance to biotite flakes. In such rocks the sporadic segregation of micropegmatite often gives rise to lighter coloured pink or white patches. The acid pink veins which traverse most of the quartz-dolerites rarely exceed an inch or two in breadth and are inconstant in their directions, as are the black basaltic veins found in both quartz-dolerites and tholeiites, though in some cases a tendency towards parallelism with the margins may be detected. Many of the quartz-dolerites are distinctly coarser than the normal Whin Sill type, but there seems to be a complete absence of the pegmatitic phase which is prominent in parts of the north of England intrusions.[1]

Quartz-dolerites.

Normal quartz-dolerite.—The microscopic characters of the quartz-dolerites have been so frequently and so fully described that little space will be devoted to them. They do not present much variation, on the whole, apart from changes in the proportion of micropegmatite. The presence of this constituent in any abundance has, however, a marked influence on the texture, for in these granophyric varieties both the plagioclase and the pyroxene crystals may become idiomorphic while there is a tendency towards elongation and curvature on the part of the latter mineral. Apatite is abundant in such rocks.

The proportion of hornblende and biotite, though never large, is also very variable and does not appear to have any connexion with the relative proportions of the other minerals. Professor W. W. Watts, writing in 'Ancient volcanoes of Great Britain' (9, vol. 1, p. 418), divides the quartz-dolerites into the Ratho type with relatively little mesostasis and the Bowden Hill type with much more. In the table of micrometric analyses given below the rocks of Hound Point (pl. v, fig. 1), North Queensferry, Laroch Hill, and Devonshaw are examples of the Ratho type (the type rock is unfortunately too much altered for accurate measurement), while the Bowden Hill type is represented by the rock of Kettlestoun quarry. The analysed rock of Auchterarder (pl. v, fig. 2) is of slightly different appearance to the foregoing and bears a close resemblance to parts of the Whin Sill. It is the freshest Scottish quartz-dolerite known to the author. The marginal proportions of the quartz-dolerite intrusions become

[1] S. I. Tomkeieff, A contribution to the petrology of the Whin Sill. Min. Mag., 1929, vol. 21, pp. 122–127.

tholeiitic in character through failure of the micropegmatite to crystallize, while the rock of the actual contact is usually of basaltic texture.

Acid veins.—The thin, light-coloured acid veins in the quartz-dolerites are nearly always much decomposed. Some of the freshest are seen under the microscope to consist of alkali-felspar (mainly orthoclase) and quartz occasionally in micropegmatitic intergrowth, but more often exhibiting microgranitic texture. Scraps of decomposed ferromagnesian minerals are of sparse occurrence and very rarely reveal themselves as elongated crystals of augite or hornblende.

Tholeiites.

The tholeiites closely resemble the quartz-dolerites in texture and mineralogical composition and differ from them microscopically only in the following particulars:

(1) No micropegmatite is found in the mesostasis of the tholeiites which is of glassy or cryptocrystalline nature.

(2) The earlier ferromagnesian minerals of the tholeiites are invariably decomposed.

For convenience of reference in this paper they may be divided into three types:

Bankhead type.—The tholeiites of Bankhead Cottages (at Dalmeny) and Kinkell quarry near Kirkintilloch (36) stand out from all others in the suite in virtue of their abundant unaltered glass and considerable proportion of chlorophaeite, which is of late crystallization and apparently primary. These characters link them with the Lower Carboniferous Dalmahoy type of tholeiite,[1] but this earlier group is distinctly more alkaline in character, and the type name cannot be therefore applied to the rocks of Dalmeny and Kinkell.

The type found in the northern portion of the working face of Kinkell quarry contains no chlorophaeite, but the glassy base is crowded with lattices of ilmenite. It is apparently unique in character. Both the Dalmeny and southern Kinkell rocks have been analysed. They differ markedly from all the Tertiary tholeiites in texture and chemical composition.

Corsiehill type (pl. v, fig. 3).—The rock of the 60-foot E.-W. dike of Corsiehill quarry north of Perth is very well preserved and proves

[1] R. Campbell and J. W. Lunn, The tholeiites and dolerites of the Dalmahoy syncline. Trans. Roy. Soc. Edinburgh, 1927, vol. 55, pp. 495–497.

under the microscope to be poor in glassy mesostasis but rich in monoclinic pyroxene. In texture it resembles the Ratho type of quartz-dolerite, but the early ferromagnesian mineral, which appears to be mainly hypersthene, is represented by pseudomorphs in serpentine. Olivine may also have been present originally, for a few lozenge-shaped pseudomorphs may be detected. This is the coarsest and most basic type of the tholeiites. It has been analysed and differs again from all the Tertiary types.

Newton Hill type (pl. v, fig. 5).—The E.–W. dike which runs along the north face of Newton Hill in north Fife is another well-preserved basic type. It is somewhat finer in grain than the Corsiehill type, and is distinctly richer in glassy mesostasis. In several ways it resembles the Bankhead type, for it contains a fair proportion of chlorophaeite, but the mineral is not primary and appears to represent olivine of early crystallization. In many examples of this type the place of chlorophaeite is taken by serpentine. The Craigmakerran type of tholeiite (38, p. 8) is practically identical to that of Newton Hill which, however, has been analysed.

Basalt Veins.

The black basaltic veins which occur in tholeiites and quartz-dolerites alike present considerable variety of texture. They are all porphyritic containing idiomorphic phenocrysts of labradorite, pyroxene, and sometimes olivine, but the groundmass may be a holocrystalline mass of minute plagioclase laths together with tiny augite granules and octahedra of magnetite, or it may be merely an indeterminate dark aggregate often almost opaque. The pyroxene is generally the normal variety of the coarser rocks, but in the basalt of Binny Craig (33, pp. 74–78) the phenocrysts sometimes contain a central rod of rhombic pyroxene. In this intrusion the basaltic phase is actually more abundant than the associated dolerite—a sharp unchilled junction occurring between the two modifications.

Hydrothermal Alteration.

Many of the more decomposed rocks have undergone the usual processes of chemical weathering, but in others there are distinct signs of hydrothermal action. This generally takes the form of albitization of the plagioclase and in such cases the ferromagnesian minerals are almost entirely altered—usually to calcite. In Fifeshire, however, a different process is seen in many of the great quartz-dolerite sills which form the Riggin or backbone of the county from the Lomonds to St. Andrews. Here the plagioclase has undergone a patchy analcimization akin to that seen in teschenites of the Midland Valley. The zeolite also occurs in the interstices between the plagioclase laths, but is never found in association with micropegmatite. Though all the leucocratic constituents of these rocks are much decomposed, the ferromagnesian minerals, including even the rhombic pyroxene, have frequently escaped alteration almost completely. The author (32, pp. 15–16) has suggested that the analcimization is possibly due to liquors emanating from the adjacent teschenite sills which in this district are intruded into strata up to and including Coal Measures.

Contact Alteration.

The metamorphism produced by the quartz-dolerite and tholeiite intrusions is not particularly intense. In the Midland Valley, where the country-rock is usually sandstone or shale, local hardening takes place with the production of quartzite, porcellanites, or spotted shales. If the shale is carbonaceous the igneous rock has frequently been converted to the condition of white trap more or less completely (22, pp. 311–313). In some cases the hydrocarbons have been distilled off into neighbouring sandstones, rendering them black in colour.[1] Still other distillation phenomena may be noted. At Oatridge Farm near Binny Craig (33, p. 75) vesicles in quartz-dolerite are filled with soft black petroleum which hardens on exposure to the air owing to loss of its volatile components, while in the quarry in the Ochil fault intrusion behind Tillicoultry some of the joint cracks in the dolerite were found by the author to contain a clear yellow petroleum jelly.

Where the country-rock consists of Lower Old Red Sandstones or conglomerates toughening and loss of colour is observed, but in the case of the andesites more interesting effects are sometimes seen. Thus in Corsiehill quarry Professor Shand[2] has recorded the presence of grossular amongst the contact lavas. Limestones have usually been recrystallized to saccharoidal marbles, and the Highland schist shows toughening without the production of many new minerals.

[1] D. Tait, Petroliferous sandstones in the Carboniferous rocks of Scotland. Trans. Geol. Soc. Edinburgh, 1928, vol. 12, pp. 90–104.

[2] S. J. Shand, Note upon crystals of grossularite from Corsiehill quarry. Trans. Perth Soc. Nat. Sci., 1908, vol. 4, pp. 210–212.

5. Distribution of Types.

The quartz-dolerites find their strongest development in the southern dike swarm and its associated sill complexes, including the great group stretching through Denny to Stirling. Here both Ratho and Bowden Hill types are found, the latter being particularly prominent among the sills of the Bathgate Hills. Tholeiites are distinctly rare as individuals in the thin southern group of intrusions, and are largely confined to the rapidly cooled margins of the quartz-dolerites. The rocks of Dalmeny and Kinkell quarry are notable exceptions.

In the northern swarm quartz-dolerites of Ratho type are abundant in the most southerly dikes and the associated sills of Fife and Kinross, but many of the sills in the former county exhibit the curious analcimization described above. North of Perth, however, tholeiites occur almost to the exclusion of quartz-dolerites in the northern swarm. They belong either to the Corsiehill or Newton Hill types, between which there is a gradational passage with increase of mesostasis. Neither type can be said to predominate in any one district.

The tholeiites in the Highland Border zone along western Strathmore have been referred to the Salen type by Dr. D. A. Allan (34, p. 87), but the author cannot confirm this determination and would place them rather in the Newton Hill type which is considerably less mafic. Neither can he agree with the inclusion of the Lornty rock by Drs. McLintock and Phemister[1] amongst the tholeiites of Brunton type, for his slides of this intrusion bear no resemblance to the type rock. It is closest to the Newton Hill type, from which it differs by being markedly porphyritic.

The dikes of Aberdeenshire are mainly tholeiitic in character, the analysed rock of Auchenbradie quarry (28, p. 164) being very similar to the Newton Hill type rock, as are the other tholeiites of this district.

The type names, 'Bankhead', 'Corsiehill', and 'Newton Hill', have been coined merely for convenience of reference in this paper. They are not intended for general application, as the literature of British tholeiites (particularly those of Tertiary age) is already overburdened by the multiplicity of types.

[1] W. F. P. McLintock and J. Phemister, On a magnetic survey over the Lornty dyke, Blairgowrie, Perthshire. Mem. Geol. Survey, Summary of Progress for 1930, part 3, p. 24.

6. Micrometric Data.

The mineral composition by volume of fourteen typical quartz-dolerites and tholeiites was measured with the aid of a Wentworth recording micrometer and the results are given in table I together with the average and maximum lengths of the plageoclase laths and the colour ratio. Apatite was not measured along with the other constituents. It occurs in proportions between 0·5 and 1·0 % in most cases.

Table I. *Mineralogical composition (by volume) and grain of quartz-dolerites and tholeiites.*

	Plagio-clase.	Augite.	Hyper-sthene.	Iron-ore.	Meso-stasis.	Maximum length of plagio-clase, mm.	Average length of plagio-clase, mm.	Colour ratio.
1.	54·6	23·4	3·1	7·9	10·0	1·5	0·8	35·4
2.	45·7	22·7	13·5	8·1	9·2	1·5	0·7	45·1
3.	45·0	24·8	11·7	6·2	12·3	2·5	1·0	42·7
4.	37·9	17·2	9·0	10·2	25·0	2·5	1·2	37·1
5.	45·2	22·6	17·3	6·8	8·1	2·0	1·0	46·7
6.	47·1	27·5	7·1	10·0	8·3	2·0	1·0	44·6
7.	41·6	23·5	12·4	8.2	14·3	2·2	0·9	44·1
Average	45·3	23·1	10·6	8·2	12·4	2·0	0·9	42·2
8.	46·1	27·7	4·8	9·2	12·2	2·0	1·0	41·7
9.	50·6	28·6	8·3	6·5	6·2	2·0	1·0	43·4
10.	44·6	29·2	6·7	6·4	13·1	1·2	0·6	42·3
11.	36·8	22·7	10·9	8·9	20·7	1·2	0·6	42·5
12.	28·3	22·4	7·0	10·8	31·5	2·0	0·9	40·2
13.	47·1	28·2	3·5	8·4	12·8	1·0	0·4	40·1
14.	38·7	26·3	5·7	9·1	20·7	1·0	0·5	41·1
Average	41·3	26·5	6·8	8·6	16·8	1·5	0·7	41·6
Total average	43·3	24·8	8·7	8·4	14·6	1·8	0·8	41 9

Quartz-dolerites.—

1. Auchterarder Station, Perthshire (dike).
2. Devonshaw quarry, Kinross-shire (sill).
3. 1 mile south of Hound Point, Midlothian (sill).
4. Kettlestoun quarry, W. Lothian (sill).
5. Kinneston Craigs, Fife (sill).
6. Laroch Hill, Argyllshire (dike).
7. N. Queensferry quarry, Fife (sill).

Tholeiites.—

8. Auchenbradie quarry, Aberdeenshire (dike).
9. Corsiehill quarry, Perthshire (dike).
10. Craigmakerran, Perthshire (dike).
11. Dalmeny Station, W. Lothian (sill).
12. Kinkell quarry, Dumbartonshire (dike).
13. Lornty quarry, Perthshire (dike).
14. Newton Hill quarry, Fife (dike).

Nos. 1, 2, and 4 contain about 1·0 % of biotite and hornblende.

The figures for hypersthene in the tholeiites probably include some olivine in many cases.

The micrometric data given above show clearly that the quartz-dolerites and tholeiites are of very similar mineralogical composition, as are the dikes and sills. Such differences as do occur may probably be accounted for by varying physical conditions at the time of intrusion. Thus the tholeiites are of slightly finer grain than the quartz-dolerites and probably underwent more rapid cooling, which doubtless accounted for the glassy character of their base. In both quartz-dolerites and tholeiites there seems to be an antipathetic relationship between the proportions of mesostasis and pyroxene.

7. Chemical Data.

Four new chemical analyses were made for this paper—two of tholeiites, one of a quartz-dolerite, and one of the residual glass isolated from a tholeiite. They are given in table II together with the norms and specific gravities.

Table II. *New analyses.*

Analyses.

	(1).	(2).	(3).	(4).
SiO_2	49·36	47·39	47·69	66·80
TiO_2	1·97	2·17	4·17	0·18
Al_2O_3	13·77	11·81	11·25	12·10
Fe_2O_3	5·35	5·71	5·37	0·97
FeO	8·03	9·58	9·84	1·50
MnO	0·19	0·26	0·29	—
MgO	5·90	6·31	5·70	0·50
CaO	9·09	11·04	9·91	2·62
Na_2O	2·11	2·28	1·81	2·40
K_2O	0·98	0·66	0·84	4·20
H_2O+	1·31	1·24	1·83	5·75
H_2O-	1·18	1·25	0·62	3·00
P_2O_5	0·44	0·60	0·42	0·39
	99·68	100·30	99·74	100·41
Specific gravity ...	2·90	2·96	2·88	2·38

Norms.

	(1).	(2).	(3).	(4).
Quartz	6·5	2·3	7·7	30·7
Orthoclase	6·1	3·9	5·0	25·0
Albite	17·8	19·4	15·2	20·4
Anorthite	25·0	20·0	20·3	10·0
Diopside $CaSiO_3$ ...	7·3	13·0	10·9	0·1
Diopside $MgSiO_3$ ...	2·2	4·8	3·0	0·1
Diopside $FeSiO_3$ ...	4·6	7·6	6·8	0·1
Hypersthene $MgSiO_3$	5·0	5·0	3·8	1·2
Hypersthene $FeSiO_3$	10·1	8·2	7·5	1·3
Magnetite	7·9	8·4	7·9	1·4
Ilmenite	3·8	4·1	7·9	0·5
Apatite	1·0	1·3	1·0	1·0
Water	2·5	2·5	2·5	8·7
	99·8	100·5	99·5	100·5

(1) Quartz-dolerite, centre of dike, quarry at Auchterarder Station, Perthshire. Analyst, N. Sahlbom.

(2) Tholeiite, centre of dike, Corsiehill quarry, one mile west of Perth. Analyst, N. Sahlbom.

(3) Tholeiite, centre of dike, Newton Hill quarry, north face of Newton Hill, Wormit, Fife. Analyst, N. Sahlbom.

(4) Glass isolated from analysed tholeiite, *Kinkell quarry, Kirkintilloch*, Dumbartonshire (35, p. 372). Analyst, F. Herdsman.

All the existing superior analyses of Scottish quartz-dolerites, tholeiites, and their segregation veins are given in tables III and IV together with averages and other analyses for comparison. Any analysis the accuracy of which is at all questionable has been rejected.

TABLE III. *Chemical analysis of normal quartz-dolerites and tholeiites.*

	Quartz-dolerites.					
	(1).	(2).	(3).	(4).	(5).	(6).
SiO_2	49·36	48·50	47·75	49·87	49·08	48·02
TiO_2	1·97	2·00	2·17	2·96	2·37	3·36
Al_2O_3	13·77	13·56	13·98	14·61	12·70	13·03
Fe_2O_3	5·35	6·59	6·33	5·21	4·77	2·11
FeO	8·03	7·08	8·29	7·65	10·05	9·99
MnO	0·19	—	—	trace	—	trace
MgO	5·90	5·15	4·84	5·90	5·58	4·21
CaO	9·09	9·24	8·05	8·70	5·70	9·77
Na_2O	2·11	2·69	2·93	2·78	3·17	2·17
K_2O	0·98	0·89	0·70	0·66	1·31	0·49
H_2O+	1·31	} 3·21	3·27	1·23	3·86	4·27
H_2O-	1·18					1·05
P_2O_5	0·44	0·49	0·27	0·36	0·59	0·40
&c.	—	0·63	1·54	0·26	0·91	1·30
	99·68	100·03	100·12	100·19	100·09	100·17

	Tholeiites.					
	(7).	(8).	(9).	(10).	(11).	(12).
SiO_2	50·78	50·12	47·39	50·44	49·10	47·69
TiO_2	2·92	2·45	2·17	3·04	4·02	4·17
Al_2O_3	11·37	14·89	11·81	11·60	12·13	11·25
Fe_2O_3	3·27	2·78	5·71	6·29	4·61	5·37
FeO	10·72	9·96	9·58	6·16	8·92	9·84
MnO	0·26	trace	0·26	0·10	0·15	0·29
MgO	5·12	5·44	6·31	5·18	4·50	5·70
CaO	9·62	8·82	11·04	9·03	8·20	9·91
Na_2O	2·31	2·05	2·28	1·97	2·14	1·81
K_2O	0·70	1·25	0·66	1·33	2·10	0·84
H_2O+	0·86	0·90	1·24	2·70	2·50	1·83
H_2O-	0·77	1·00	1·25	1·59	1·02	0·62
P_2O_5	0·21	0·23	0·60	0·38	0·51	0·42
&c.	1·14	—	—	0·21	0·03	—
	100·05	99·89	100·30	100·02	99·93	99·74

TABLE IV. *Chemical analysis of segregation veins, average analyses and other analyses for comparison.*

	(13).	(14).	(15).	(A).	(16).	(17).
SiO_2	59·33	64·54	69·57	65·20	48·8	49·3
TiO_2	3·42	1·22	0·65	0·39	2·5	3·1
Al_2O_3	12·86	13·63	13·03	13·72	13·6	12·2
Fe_2O_3	1·88	0·22	0·98	3·63	5·1	4·7
FeO	6·46	4·83	3·59	3·72	8·5	9·2
MnO	0·14	0·20	—	—	—	0·2
MgO	2·09	1·25	1·06	1·01	5·3	5·5
CaO	3·74	2·31	1·56	2·79	8·4	9·4
Na_2O	5·13	5·21	4·57	5·22	2·6	2·1
K_2O	2·15	2·28	2·37	2·17	0·8	1·1
H_2O+	2·12	1·86	2·04 (H₂O+ and H₂O−)	1·27	3·2 (H₂O+ and H₂O−)	2·7 (H₂O+ and H₂O−)
H_2O-	0·48	0·84		0·72		
P_2O_5	0·39	0·32	0·47	0·38	0·4	0·4
&c.	0·26	1·79	0·89	—	0·8	0·2
	100·45	100·50	100·78	100·22	100·0	100·1

	(18).	(B).	(C).	(D).	(E).
SiO_2	49·0	50·52	48·79	49·68	46·2
TiO_2	2·8	2·39	4·17	2·60	2·4
Al_2O_3	12·9	13·76	11·96	12·95	13·7
Fe_2O_3	4·9	3·87	2·51	3·47	2·1
FeO	8·9	8·50	12·10	10·10	9·2
MnO	0·1	0·16	0·21	0·20	0·2
MgO	5·4	5·42	5·60	5·69	9·6
CaO	8·9	9·09	10·15	10·09	9·8
Na_2O	2·4	2·42	2·40	2·27	2·6
K_2O	1·0	0·96	0·70	0·52	1·4
H_2O+	3·0 (H₂O+ and H₂O−)	1·51	1·05 (H₂O+ and H₂O−)	1·71	1·6
H_2O-		0·76		0·29	0·4
P_2O_5	0·4	0·26	0·37	0·33	0·5
&c.	0·5	0·69	—	0·04	0·2
	100·2	100·31	100·01	99·94	99·9

(1) Quartz-dolerite, centre of dike, quarry at Auchterarder Station, Perthshire. Analyst, N. Sahlbom. New Analysis.

(2) Quartz-dolerite, Hound Point sill, Dalmeny, West Lothian. Analyst, T. C. Day. Quoted from T. C. Day, Trans. Geol. Soc. Edinburgh, 1928, vol. 12, p. 85.

(3) Quartz-dolerite close to segregation vein at same locality. Analyst, T. C. Day (loc. cit.).

(4) Quartz-dolerite, North Queensferry sill, Fife. Analysts, J. B. Harrison and Reid. Quoted from U.S. Geol. Survey Prof. Paper 99, 1917, p. 649.

(5) Quartz-dolerite, Ferrytoll quarry, North Queensferry sill. Analyst, T. C. Day (loc. cit.).

(6) Quartz-dolerite sill at Kettlestoun quarry, Bathgate Hills, West Lothian. Analyst, G. S. Blake. Quoted from (15, p. 147).

(7) Tholeiite, dike in Auchenbradie quarry, Insch, Aberdeenshire. Analyst, E. G. Radley. Quoted from (28, p. 164).

(8) Basaltic tholeiite, Binny Craig sill, West Lothian. Analyst, W. H. Herdsman. Quoted from (33, p. 78).

(9) Tholeiite, dike in Corsiehill quarry, Perthshire. Analyst, N. Sahlbom. New Analysis.

(10) Tholeiite, sill in railway cutting, Dalmeny, West Lothian. Analyst, J. Jakob. Quoted from (36, p. 370).

(11) Tholeiite, dike in Kinkell quarry, Kirkintilloch, Dumbartonshire. Analyst, J. Jakob. Quoted from (36, p. 372).

(12) Tholeiite, dike in quarry on north face of Newton Hill, Wormit, Fife. Analyst, N. Sahlbom. New Analysis.

(13) Felspathic quartz-dolerite, sill at Kettlestoun quarry, Bathgate Hills, West Lothian. Analyst, G. S. Blake. Quoted from (15, p. 147).

(14) Segregation vein (blue band) in quartz-dolerite, sill at Caribber quarry, Bathgate Hills, West Lothian. Analyst, G. S. Blake. Loc. cit. supra.

(15) Segregation vein in quartz-dolerite, sill at Ferrytoll quarry, North Queensferry, Fife. T. C. Day, Analyst. Quoted from T. C. Day, Trans. Geol. Soc. Edinburgh, 1928, vol. 12, p. 85.

(A) Felsitic vein in Whin Sill, Alnwick Moor, Northumberland. Analyst, S. I. Tomkeieff. Quoted from Min. Mag., 1929, vol. 22, p. 110.

(16) Average Scottish quartz-dolerite.

(17) Average Scottish tholeiite.

(18) Average of Scottish quartz-dolerites and tholeiites.

(B) Average Whin Sill magma. Quoted from A. Holmes and H. F. Harwood (loc. cit., p. 539),

(C) Basalt, Holmatindur, Iceland. Analyst, H. F. Harwood. Quoted from A. Holmes, Min. Mag., 1918. vol. 18, p. 192.

(D) Average Deccan basalt. Quoted from A. Holmes, Min. Mag., 1928, vol. 21, p. 539.

(E) Average of three analyses of basalt of Dalmeny type taken from The geology of north Ayrshire, Mem. Geol. Survey, 1930, p. 106.

The chemical data, like the micrometric, show that, apart from segregation veins and patches, there is little variation in the composition of the normal quartz-dolerites and tholeiites of Scotland. The Scottish tholeiites have a slightly lower alumina percentage than the quartz-dolerites and seem to be a little richer in potash, but there the difference ends. Indeed the essential similarity of the two types is far more striking than these slight variations. The new analyses agree well with those published previously.

The average chemical composition of the Scottish rocks is slightly more basic than that of the average Whin Sill type in the north of England, but again the strong resemblance is much more marked than the difference. The quartz-dolerite of Auchterarder Station especially, which is very similar microscopically to the Whin Sill type, shows an equally close chemical resemblance. It seems, therefore, certain that the north of England intrusions and the Scottish quartz-dolerites and tholeiites are co-magmatic, the conclusions reached by the field evidence being firmly supported by the chemical data.

The analyses of the Scottish rocks may be well matched by the average Deccan basalt and by a plateau basalt from Iceland.

All the Scottish quartz-dolerites and tholeiites appear to be just over the saturation point with silica, the residue, when fresh, being in all cases siliceous. Even in the most basic analysis—that of Corsiehill—2·3 % of normative quartz was recorded.

The chemical resemblance of the quartz-dolerites and tholeiites of Scotland to those of the Whin Sill group of the north of England extends to the acid segregation veins and also to the later basaltic injections which have in both areas practically the same composition as the normal rock. In the case of the acid veins the close resemblance may be seen by comparison of analyses 14 and A which show excellent agreement.

The chemical composition of the residual liquid.

In recent years there has been a certain amount of discussion as to the chemical composition of the residual liquids of basalts and dolerites. Dr. C. N. Fenner[1] has expressed the opinion that the micrographic and myrmekitic intergrowths found in many doleritic intrusions are the result of chemical action of late hydrothermal solutions and cannot be regarded as primary constituents of the magma. He has stated further that the low refractive indices recorded for the residual glasses of basalts of tholeiitic composition are due to the presence of borates, fluorides, and phosphates, and that they are rich in iron oxide and not of dacitic composition as the figures would indicate.

In describing two tholeiitic members of the suite now under consideration, the author (36, pp. 374–376) gave reasons for opposing this view. He showed that the residual glass of these tholeiites had a refractive index (1·495) corresponding to that of rhyolitic obsidian, that the glass contained no noteworthy proportions of phosphates and fluorides, and that the presence of the small percentage of B_2O_3 actually found in the glass would probably raise the index rather than lower it. The view of Dr. Fenner that iron is

[1] C. N. Fenner, The crystallization of basalts. Amer. Journ. Sci., 1929, ser. 5, vol. 18, pp. 239–243 [M.A. 4–507].

concentrated in the residual liquids of such magmas was, however, confirmed by the detection of chlorophaeite and ilmenite of late crystallization. In a later article Dr. Fenner[1] criticized the author's result on the grounds that the rocks studied were not volcanic but deep-seated, and that the proportion of glass was relatively large. He apparently inclined towards the view that the micropegmatite of the Scottish quartz-dolerites was probably of hydrothermal origin, and that the low refractive index of the glass might still be due to the presence of halides, since the evidence adduced by the author on the point was regarded by him as insufficient.

It seemed advisable, therefore, to isolate the glass from one of the analysed tholeiites and to have a chemical analysis made of this material. After repeated separations by heavy liquids, checked at each stage by microscopic examination, an unaltered glass was obtained from the southern Kinkell rock containing less than one per cent. of impurities (mainly plagioclase and chlorophaeite). This was analysed by Mr. F. Herdsman and the results are given in the table of new analyses (p. 150). They show clearly that the glass is, as the low refractive index would indicate, highly siliceous, the percentage of SiO_2 being 72·1 if the analysis is calculated as water-free. This value is actually higher than that in the most siliceous analysis, no. 15 on p. 152, that of a pink segregation vein. In other respects the two analyses show moderate agreement. It may be therefore considered as definitely proved that the residual liquids of members of the suite under consideration are highly siliceous and might be expected accordingly to yield micropegmatite upon crystallization. The glass from the rock of the north part of the quarry has exactly the same refractive index as that isolated, but is crowded with lattices of ilmenite crystals and might for this reason be regarded as rich in iron. The author maintains, however, that the bulk of the iron is removed as chlorophaeite or iron-ore just before the solidification of the glass. In the analysis of the glass the percentage of total iron oxides, even if calculated as water-free, amounts to less than two-thirds of the corresponding percentage in the most siliceous segregation vein. The refractive index of the residual glass is then a reliable guide to its chemical composition in the case of these tholeiites, and it is unnecessary to invoke the aid of occluded halides, borates, and phosphates to account for the low refractive index. Moreover, if

[1] C. N. Fenner, The residual liquids of crystallizing magmas. Min. Mag., 1931, vol. 22, pp. 539–560.

these conclusions are applied to the co-magmatic quartz-dolerites which are of very similar chemical and mineralogical composition, there is every reason to believe that their micropegmatite is of late magmatic origin and not due to hydrothermal reactions as Dr. Fenner has suggested.

Dr. Fenner has objected that the tholeiites examined by the author contained a relatively large proportion of glass as opposed to the basalts examined by him (C.N.F.). It may be noted, however, that the glass of these tholeiites is, like the micropegmatite of the quartz-dolerites, notoriously capricious in its distribution, and that at both Dalmeny and Kinkell, not to mention numerous other localities where the glass is more or less decomposed, specimens may be found in which the proportion is quite small. With regard to Dr. Fenner's criticism that the tholeiites in question are deep-seated hypabyssal rocks, it should be observed that their grain is no coarser than that of many basalt lavas and that the mere fact that the residual liquid solidified as glass is evidence that cooling was much more rapid than is consistent with deep-seated conditions.

Confirmation, however, was obtained of Dr. Fenner's contention that there is a tendency towards concentration of the iron in the residual liquid of basalt as crystallization proceeds, for the Fe : MgO ratio in the residual glass of the Kinkell tholeiite is considerably greater than that in the normal rock.

8. Relationship of the Suite to Carboniferous volcanic Activity.

The exact connexion between the rocks of the suite and the Carboniferous volcanicity of southern Scotland is doubtful. Showing remarkably little variation in chemical composition, the quartz-dolerites and tholeiites are clearly of tholeiitic magma-type. The Carboniferous (and Permian) igneous rocks, on the other hand, are all of olivine-basalt magma-type. The micro-porphyritic Dalmeny type of olivine-basalt very probably represents the parental magma, in view of its early occurrence, uniform composition, and extended distribution (both lateral and vertical).

Comparison of analyses nos. (18) and (E) shows that the quartz-dolerite magma is poorer in alkalis than the relatively basic Dalmeny type of olivine-basalt (or any other widespread type of Carboniferous olivine-basalt) and cannot, therefore, have been derived from this magma by any process of crystallization-differentiation or gaseous transfer. Nor can the derivation be effected, as was suggested by Dr. G. W. Tyrrell (21, p. 365), by simple assimilation, for the construction of an addition and subtraction diagram proves that both the most siliceous material which could be added or the least siliceous subtracted, to give the quartz-dolerite type, have compositions far

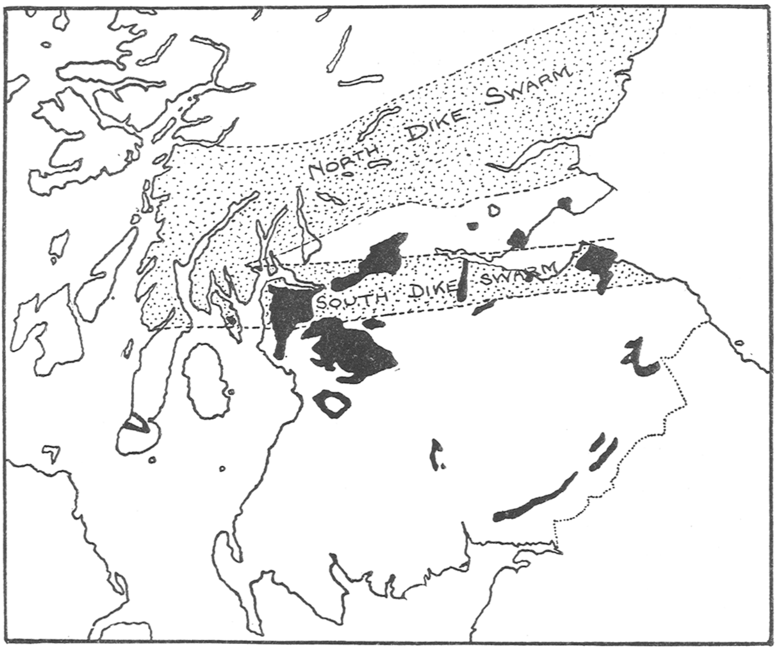

FIG. 2. Sketch-map showing relationship of quartz-dolerite and tholeiite dikes to the Carboniferous volcanic rocks.

removed from those of any known igneous or sedimentary rocks or mixture thereof. Selective assimilation of silica and iron oxide accompanied by loss of magnesia might provide a solution to the problem, but no evidence on this point can be advanced. It is conceivable, however, that such a process might have taken place if the Carboniferous olivine-basalt magma remained in contact with the lower layers of the 'sial' for a prolonged period. If this was the case, the Permo-Carboniferous earth-movements must have opened conduits to the contaminated material of the upper 'sima', allowing it to work upwards, though not, apparently, to the surface. In this connexion the restriction of the tholeiite magma-type to the 'sial' continental blocks and its absence from oceanic islands[1] is, perhaps, significant.

The sketch-map (text-fig. 2) shows that the distributions of the two suites have no close link, especially if the quartz-dolerite sills be excluded on the ground that they merely represent the lateral spread of material from the dikes controlled partly by planes of weakness in the sedimentary series and partly by the hydrostatic pressure exerted by the superincumbent rock-column. It will be seen, indeed, that the dike swarms bear no distributional relationship to any of the centres of Carboniferous volcanicity. Their occurrence appears to be controlled rather by the powerful Permo-Carboniferous earth-movements, as might be expected.

The differentiation of the two magma-types followed the course so clearly outlined by Dr. W. Q. Kennedy (loc. cit.), the alkaline differentiates of the Carboniferous olivine-basalt contrasting strongly with the calcic and granophyric products of the quartz-dolerite suite.

9. Rocks of doubtful affinities.

In Morvern the work of Mr. A. G. MacGregor and Dr. W. Q. Kennedy[2] has revealed the presence of a series of bosses of quartz-dolerite which are elongated in an E.-W. direction. These are coarse-grained rocks resembling the quartz-dolerites of the Midland Valley and they may belong to the same suite. They have brought about very considerable metamorphism of the country-rock.

There are also the Milngavie sills near Glasgow to be considered (as well as a few sills near Edinburgh) which carry neither olivine, hypersthene, nor acid mesostasis. They show affinities with both the quartz-dolerite and teschenite suites, but the nature of the pyroxene—a brownish-purple variety with 2V about 60°—links them more closely with the latter group. No dike of this type has been recorded.

10. Summary.

The E.-W. dikes of quartz-dolerite and tholeiite in Scotland and the related sills show marked resemblances, both chemical and mineralogical, to the Whin Sill in the north of England. They appear to belong to the same period of intrusion, which is roughly coeval

[1] W. Q. Kennedy, loc. cit., p. 249.

[2] A. G. MacGregor and W. Q. Kennedy, The Morvern-Strontian granite. Mem Geol. Survey, Summary of Progress for 1931, part 2, p. 105.

with the Permo-Carboniferous folding and faulting. Chemical analyses of an unaltered residual glass in one of the tholeiites shows it to be highly siliceous, and there is therefore no reason for considering the micropegmatite of the very similar quartz-dolerites to be other than magmatic. It is suggested that the suite may have arisen through mild contamination of the parental Carboniferous olivine-basalt magma by prolonged contact with the 'sial'.

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Explanation of Plate V.

Quartz-dolerites and tholeiites.

Fig. 1. Quartz-dolerite, centre of sill, Hound Point, West Lothian. Ordinary light, ×15. Laths of plagioclase show subidiomorphic relationship with diopsidic pyroxene. A few crystals of titanomagnetite are conspicuous, and a prism of hypersthene occurs in the bottom left-hand quadrant. A little turbid micropegmatite fills the interstices between the felspar.

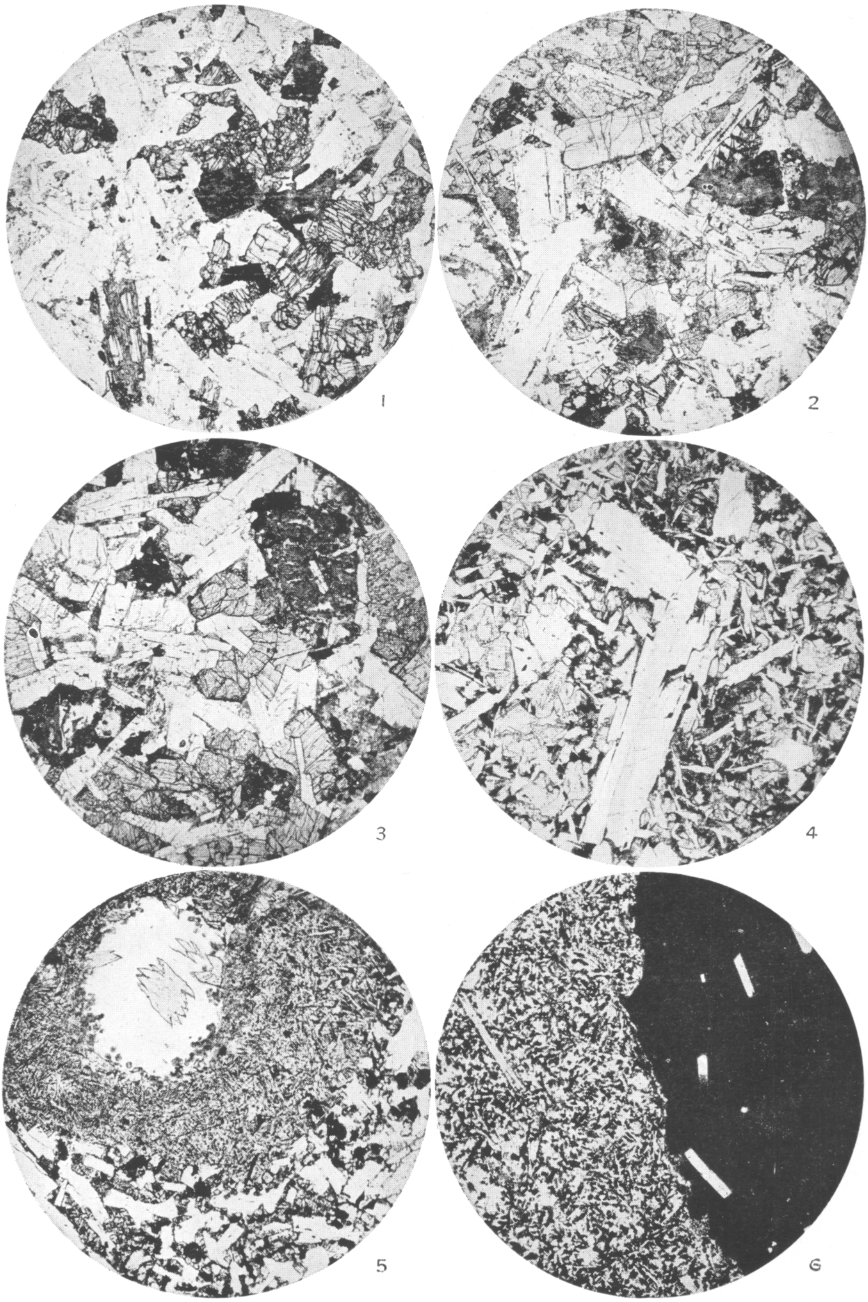
Fig. 2. Quartz-dolerite, centre of dike, Auchterarder Station, Perthshire. Ordinary light, ×16⅔. A similar rock to fig. 1, but with texture closer to the normal rock of the Whin Sill.

Fig. 3. Tholeiite, centre of dike, Corsiehill quarry, Perthshire. Ordinary light. ×16⅔. Similar to figs. 1 and 2, but the place of micropegmatite is taken by devitrified glass, and that of hypersthene by conspicuous pseudomorphs in serpentine.

Fig. 4. Tholeiite, quarry at west end of dike, Lornty, Perthshire. Ordinary light, ×16⅔. Phenocrysts of basic labradorite are conspicuous in a groundmass of labradorite laths, sub-ophitic pyroxene, titanomagnetite, and mesostasis.

Fig. 5. Tholeiite, quarry in dike, on north face of Newton Hill, Fife. Ordinary light, ×15. Part of a circular vesicle with a glassy margin and a centre of quartz and calcite fills most of the field. The remainder consists of plagioclase laths, sub-ophitic pyroxene, titanomagnetite, and devitrified glass.

Fig. 6. Basalt vein in quartz-dolerite sill. Greenhill Farm, Fife. Ordinary light, ×16⅔. A black basaltic vein containing a few phenocrysts of plagioclase is seen to be chilled against a fine-grained decomposed quartz-dolerite or tholeiite.



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