THE MINERALOGICAL MAGAZINE

AND

JOURNAL OF

THE MINERALOGICAL SOCIETY.

No. 122. September, 1928. Vol. XXI.

The age and composition of the Whin Sill and the related dikes of the north of England.[1]

(*With Plate X.*)

By ARTHUR HOLMES, D.Sc., A.R.C.S., F.G.S.
Professor of Geology, The University, Durham,
and H. F. HARWOOD, M.Sc., Ph.D., A.I.C.
Lecturer in Chemistry, Imperial College, London.

[Read March 20, 1928.]

CONTENTS.

---

[1] The chemical analyses and calculations of norms have been made by Dr. Harwood. The field work and petrological investigations have been carried out by Professor Holmes, who is also responsible for the writing of the paper.

1. Introduction and Literature.

THE system of intrusive sheets in the Lower Carboniferous formations of the north of England, familiar to geologists throughout the world as the Great Whin Sill, has a voluminous early literature which it is unnecessary to summarize here. It will be sufficient to refer to the classical papers by Topley and Lebour on the field relationships (**1**) and by Teall on the detailed petrography (**4**), each of which contains an ample bibliography of the earlier literature. The most recent general account is by Prof. E. J. Garwood (**9**), who contributed a careful discussion of the evidence bearing on the period of intrusion.

Teall's great paper closely followed on one devoted to some of the dikes of the north of England (**3**), and in it he drew attention to the remarkable petrographical similarity between the rocks of the Hett and High Green dikes and that of the Whin Sill (**4**, p. 656). Unfortunately the striking similarity did not appear to extend to the chemical composition of the three sets of rocks, the reason being, as we now know, that the analyses of some of the dike-rocks (carried out in the laboratories of the late Sir I. Lothian Bell in 1875 and in those of the late J. E. Stead in 1884) fell seriously short of modern standards, and thus gave a misleading picture of variation that is far from being reflected in the characters of the rocks themselves (**3**; **4**; and **7**, p. 453). The analyses of the Whin Sill made by Teall himself have been completely confirmed by all later work (see page 513), and show that his efficiency as a rock analyst was worthy of his genius as a petrologist. Had Teall made similar analyses of the Hett and High Green rocks the results would undoubtedly have confirmed his opinion of the material identity of these rocks with that of the Whin Sill, and would thus have fortified his inclination to regard both dikes and sills as simultaneous intrusions.

The post-Westphalian dikes of the north of England may be classified by their orientations into two clearly defined series. One of these consists of quartz-dolerites of the Whin Sill type, and includes the dikes already referred to. The dikes run east and west or north of east, and many of them fall naturally into well-marked echelons as shown on the accompanying sketch-map, fig. 1. The most northerly echelon, of which the Holy Island dike is the best known member, was not described by Teall. The second echelon includes the High Green dikes. The third stretches from Haltwhistle to Causey Park, and part of it was described by Lebour as the 'Brunton' dike. Teall described what he was led to believe was a specimen of this dike, but, as we shall show, his 'Brunton type', as it has since been called by the Geological Survey, is really a tholeiite from the little Bingfield dike, the chief exposure of which lies not far off the line of the St. Oswald's Chapel dike. Actually, none of the dikes of the third echelon has hitherto been petrologically described. The fourth system of dikes includes the well-known Hett dike.

The Bingfield dike is a member of a quite different series, which includes the Acklington and Cleveland dikes and a set of roughly parallel dikes lying between these two. The dikes of this series consist of tholeiites of related types; they run north of west, and are presumably of Tertiary age. Although they appear to converge towards Arran and Bute, their Scottish continuations swing round so as to pass by way of Great Cumbrae and the adjoining parts of Ayrshire and Cowal into the Mull dike-swarm. The salient features which distinguish them from the Whin Sill group have already been clearly stated by Mr. G. S. Mockler (25). In a later paper we propose to record the composition of some of the chief representatives of the tholeiite dikes. The present contribution is mainly devoted to rocks of the Whin Sill type. The collection of rocks on which the work is based includes many of the specimens collected by Teall. These were appropriately presented to the Geological Department of the Durham Colleges by Lady Teall in 1925.

Literature.

1 1877 Topley (W.) and Lebour (G. A.). On the intrusive character of the Whin Sill. Quart. Journ. Geol. Soc. London, vol. 33, pp. 406–421.

2 1878 Lebour (G. A.). Outlines of the geology of Northumberland. (Newcastle-upon-Tyne, 1878.)

3 1884 Teall (J. J. H.). Petrological notes on some north-of-England dykes. Quart. Journ. Geol. Soc. London, vol. 40, pp. 209–247.

4 1884 Teall (J. J. H.). On the chemical and microscopical characters of the Whin Sill (with bibliography of earlier literature). Quart. Journ. Geol. Soc. London, vol. 40, pp. 640–657.

5 1886 Lebour (G. A.). Outlines of the geology of Northumberland and Durham. (Newcastle-upon-Tyne, 1886.)

6 1887 Mem. Geol. Survey, England and Wales. Otterburn and Elsdon.

7 1888 Teall (J. J. H.). British Petrography. (London, 1888), pp. 200–209.

8 1889 Mem. Geol. Survey, England and Wales. The geology of Plashetts and Kielder.

9 1910 Garwood (E. J.). Northumberland and Durham. Geology in the Field, Geol. Assoc. Jubilee volume, pp. 688–694.

10 1910 Finlayson (A. M.). Problems of ore-deposition in the lead and zinc veins of Great Britain. Quart. Journ. Geol. Soc. London, vol. 66, pp. 293–327.

11 1911 WEYMAN (G.). On the section of the Great Whin Sill near Gunnerton. Proc. Univ. Durham Phil. Soc., vol. 3, pp. 201-205.

12 1912 HESLOP (Mary K.). A preliminary note on the uniaxial augites of the north of England igneous dykes. Proc. Univ. Durham Phil. Soc., vol. 4, pp. 172-174.

13 1913 WEYMAN (G.). The Great Whin Sill at Kirkwhelpington. Proc. Univ. Durham Phil. Soc., vol. 5, pp. 63-67.

14 1914 SMYTHE (J. A.). Inclusions in the Great Whin Sill of Northumberland. Geol. Mag., 1914, dec. 6, vol. 1, pp. 244-255.

15 1921 HOLMES (A.) and SMITH (S.). The Wackerfield dyke, County Durham. Geol. Mag., 1921, vol. 58, pp. 440-454.

16 1922 SMYTHE (J. A.). Minerals of the north country: barium minerals. The Vasculum, Newcastle-upon-Tyne, vol. 8, pp. 90-93, 113-116.

17 1923 WOOLACOTT (D.). A boring at Roddymoor Colliery, near Crook, Co Durham. Geol. Mag., 1923, vol. 60, pp. 50-62.

18 1923 SMITH (Stanley). Lead and zinc ores of Northumberland and Alston Moor. Mem. Geol. Survey, Spec. Rep. Min. Resources Great Britain, vol. 25.

19 1923 CARRUTHERS (R. G.) and STRAHAN (A.). Lead and zinc ores of Durham, Yorkshire, and Derbyshire. Mem. Geol. Survey, Spec. Rep. Min. Resources Great Britain, vol. 26.

20 1924 SMYTHE (J. A.). Minerals of the north country: silicates. The Vasculum, Newcastle-upon-Tyne, vol. 10, pp. 100-103.

21 1924 Summary of Progress of the Geol. Survey of Great Britain for 1923, pp. 84-86, fig. 5.

22 1926 GILLIGAN (A.). The geology of the Appleby district. (Appleby, 1926.)

23 1927 Mem. Geol. Survey, England and Wales. The Geology of Belford, Holy Island, and the Farne Islands. 2nd edition.

24 1927 TURNER (J. S.). The Lower Carboniferous succession in the Westmorland Pennines and the relations of the Pennine and Dent faults. Proc. Geol. Assoc. London, vol. 38, pp. 339-374.

25 1927 MOCKLER (G. S.). A preliminary account of the dykes of Northumberland. Proc. Univ. Durham Phil. Soc., vol. 7, pp. 244-245.

26 1927 VERSEY (H. C.). Post-Carboniferous movements in the Northumbrian fault block. Proc. Yorkshire Geol. Soc., vol. 21, pp. 1-16.

2. GENERAL SURVEY.

A good account of the northern section of the Whin Sill was given a year ago by the Geological Survey **(23)**. Here there occur several sheets at different horizons, ranging from low down in the Scremerston Coal Group to the Middle Limestone Group (see one-inch Geological Map, Sheet 4, 1925). The interrupted outcrops follow a crescentic course from the Kyloe Hills in the west, through Belford and Bamburgh, to the Farne Islands in the east. The chord of the crescentic arc is marked by the Holy Island echelon-series of dikes, and it is noteworthy that the

Whin Sill has not been detected north of the dikes, despite the fact that appropriate formations are exposed.

South of the Bamburgh district the Whin Sill is nowhere seen for some five miles. It then appears at Snook point, where it is only 25 feet thick, dipping towards the south-east. This exposure was described by Dr. J. A. Smythe in 1914 (**14**) with special reference to the occurrence of some very remarkable cognate inclusions, which, together with the enclosing normal rock, were chemically analysed. The Whin Sill outcrops along the coast from Dunstanborough to Cullernose and then turns inland towards Alnwick. A map of part of this section has been published by the Survey showing the relation to the east-and-west faults of the district, one of which, with a 200-foot downthrow to the north, is definitely proved to have preceded the intrusion (**21**). Beyond Alnwick the Whin Sill continues for five miles, but it fails to appear beyond the trend of the Hampeth and Flamborough dikes. These dikes are members of a long echelon-system of dikes which extends from the Lewisburn dike on the west, through the High Green dikes made familiar by Teall, past Rothbury, and on to the coast at Boulmer.

After a gap of seven miles the Whin Sill reappears beyond the Coquet and gradually becomes an increasingly conspicuous feature. Near Kirkwhelpington and Great Bavington it is strongly developed in a series of sheets at different horizons, local details of which have been recorded by Weyman (**11** and **13**). From this neighbourhood the outcrops continue with minor irregularities across the North Tyne to the bold northward-facing scarp along the crest of which the Romans built part of their great defensive wall. Here we pass the crags near Borcovicus where Teall collected a specimen for analysis. Continuing into Cumberland the Whin Sill becomes thinner, and after a few miles the outcrops suddenly turn to the south and become sporadic. From Cumberland to the Coquet gap the outcrops are approximately paralleled to the south by a third series of dikes. North-east of Kirkheaton the dikes are small and far apart, but taken as a whole the series clearly forms a third echelon.

Along the western margin of the Pennines the Whin Sill is visible as a generally conspicuous band cropping out in the valleys that notch the escarpment. In the extreme south of this section it can be traced across Swindale Beck (north-east of Roman Fell), but after becoming attenuated to about 8 feet it is sharply cut off by the Inner Pennine fault, and no outcrops to the south of the fault have yet been discovered. A description of this part of the Sill has recently been written by Prof. A. Gilligan (**22**) and a map of the region has been published by Mr. J. S. Turner (**24**). The next exposures run along the north side of Lunedale towards Middleton-in-Teesdale. The Sill is cut through by the Lunedale fault, but here a few isolated outcrops have been detected south of the fault. More interesting, however, is the possibility that the southern boundary of the Whin Sill, like the northern one, is a dike system. Beginning with two small dikes on Long Fell, and continuing through others in Lunedale, the southern tip of the widespread Whin Sill exposures in Upper Teesdale is reached. A mile or so beyond, the long Hett dike of Durham begins and runs across country and through the collieries towards the Permian escarpment. As it dies out, the running is taken up a little to the north by the parallel Ludworth dike which has been traced beneath the Permian almost to the coast. South of the Hett system the only sill that has been met with is a thin offshoot that crosses the Lune near Middleton-in-Teesdale. The little Wackerfield dike, six miles south of the Hett dike, is the most southerly example known in the north of England of a rock representing the Whin Sill magma-type. The dike has already been investigated by Dr. Stanley Smith and ourselves (**15**).

North-west of the picturesque outcrops of the Upper Tees and the well-known falls of High Force and Cauldron Snout, in the uplifted block of country between the Pennine escarpment and the nearly parallel Burtree Ford disturbances, there are many small exposures of the Whin Sill. Between Cross Fell and Rotherhope Fell the headwaters of the South Tyne have cut down to the Whin Sill, but the exposures are terminated by the 'Great Sulphur Vein', a mineralized fault-fissure with downthrow to the north. A similar set of exposures is met with near Midgeholm, sharply cut off by the Stublick faults. It is noteworthy that thin sills appear in the Millstone Grit and Coal Measures north of the Stublick faults, suggesting, as Mr. H. C. Versey has recently pointed out (**26**, p. 9), 'that some movement of these faults had taken place prior to the intrusion of the sill'. Analyses of the Whin Sill from Cauldron Snout and Rotherhope have been made by Teall (**4**) and Finlayson (**10**, p. 304) respectively.

East of the Burtree Ford disturbances the Whin Sill has been encountered in some of the lead mines (**19**), but the only outcrop known is that of the Little Whin Sill of Weardale, a subsidiary sheet which occurs on both sides of the valley west of Stanhope at a higher stratigraphical level than the main intrusion. In its most easterly known position the Whin Sill occurs in the Scar Limestone beneath Roddymoor Colliery, ten miles WSW. of Durham. Here in 1921 a deep boring was

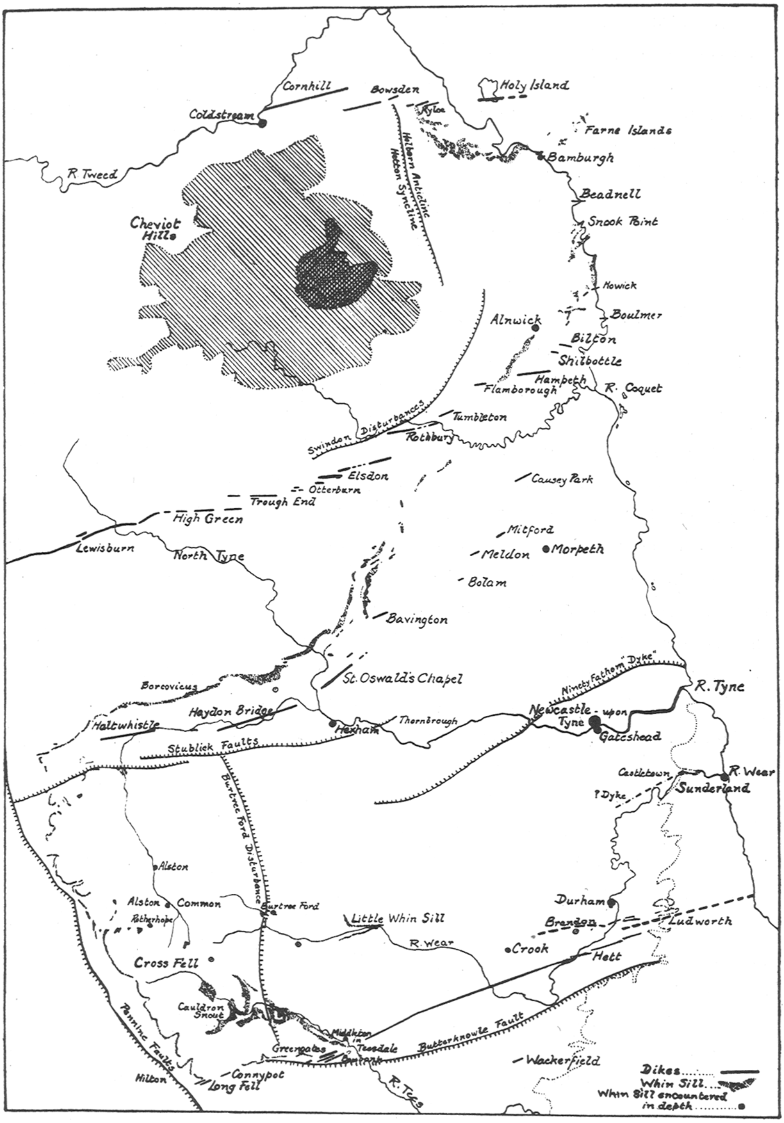


FIG. 1. Map of the Whin Sill and related dikes.

completed which passed down into what are probably Skiddaw Slates. The description of the penetrated strata by Woolacott (**17**) shows that the Whin Sill is 187 feet thick. Woolacott records other thicknesses as follows (**17**, p. 57): 'At Burtree Pasture Mine it is about 240 feet; at Carr Edge Mine, Northumberland, it is 222 feet; and in Teesdale it reaches 200 feet near Cronkley Scar. Its average thickness is from 80 to 100 feet, but it thins out westwards on the Pennine escarpment to 6 feet (Rundale Beck)'.

3. PETROLOGICAL CHARACTERS OF THE NORMAL ROCKS.

The general characters of the normal rock-type of the Whin Sill and of its compact marginal facies and coarse pegmatitic segregations have been thoroughly described by Teall (**4**, p. 642), and are so well known that they need be referred to here but briefly. The average grain size ranges from 0·2 mm. to 0·5 mm. in the fine-grained varieties and from 0·5 mm. to 1·0 mm. in those of medium grain. Apart from this difference in scale and from local peculiarities of late magmatic alteration, sections of rocks falling within this range of grain size generally present a nearly uniform appearance under the microscope. An interlacing network of plagioclase laths and of elongated or stumpy prisms of pyroxene is held together by plates and granular aggregates of augite, and conspicuously sprinkled with titano-magnetite in skeletal or well individualized forms. In smaller quantities alkali-felspar, micropegmatite, and quartz occur in the interstices; and in the more rapidly cooled varieties a vague mesostasis, charged with strings of black globulites and incipient fibrous growths of felspar and pyroxene, is present in patches which rarely exceed the grain size of the rock. Brown hornblende and biotite occur as reaction minerals. Apatite needles are a constant accessory, and specks of pyrite can often be detected. Green hornblende and various green chloritic and serpentinous substances are present in small but very variable quantities as the common alteration products. Ophitic, intergranular, and intersertal textures are all developed, and may be frequently seen side by side in one and the same section. The dike rocks generally exhibit the same assemblage of characters, but in some places they are more altered than the Whin Sill and they may contain irregular aggregates of calcite, sometimes associated with quartz, filling residual spaces but without the definite shapes and boundaries of typical amygdales. In the dikes that have risen high into the Coal Measures intersertal and irregular patches of mesostasis become a definite feature of the rocks, commonly exceeding the grain size. Some of these rocks might properly be referred to as tholeiites. Albitization and sericitization are rare, but parts of the Hampeth dike near Alnwick (**23**, p. 121) and of the Lewisburn dike (near the other end of the same echelon system) have suffered severely from one or other of these processes.

The amygdales locally found in the Whin Sill and dikes generally contain calcite with or without quartz and chlorite. Pectolite occurs as white radiating masses in vesicles in the Whin Sill of Copthill, Wearhead, and of Caw Burn, north of Haltwhistle, and in a vein near the foot of Cauldron Snout where it is associated with calcite. These occurrences are recorded by Smythe who has also analysed the specimens from Caw Burn and Cauldron Snout (**20**). Nests of amethyst and nail-head calcite are to be found in the Haydon Bridge dike, and rose-quartz has been recorded by Smythe from the Hampeth dike.

The following notes on the plagioclase and pyroxenes of the rocks of the Whin Sill type are added on account of their bearing on the history of the Whin Sill magma and its consolidation.

Felspars.—Plagioclase is the most abundant mineral in all the rocks examined. The dominant type is of prismatic habit, giving lath-shaped and squat rectangular sections. The larger prisms exhibit zoning more clearly than the smaller crystals, particularly near the beginning and towards the close of their crystallization, and it is sometimes possible to detect within them a core approximating to An_{70}. The main bulk of the crystals is generally about An_{50}, a range of An_{40} to An_{62} having been found. There is then a rapid passage to a thin external layer of oligoclase having a mean refractive index near to or slightly lower than that of Canada balsam. The average plagioclase is probably not far below An_{50}. It is noteworthy that the first felspar to crystallize from a melt of this composition would not exceed An_{78}.

Teall's analysis of the felspar from the Whin Sill of Cauldron Snout (**4**, p. 646) is by no means discordant with the above determinations, for the material separated for analysis included a certain amount of entangled interstitial matter. The bulk analysis corresponds nearly to $An_{30}\,Ab_{50}\,Or_{20}$. The actual plagioclase is unlikely to contain more than 10 per cent. of orthoclase, and the remaining orthoclase is most likely to be present in the products of a residual ternary eutectic of quartz and alkali-felspars having the approximate composition represented by the empirical formula 2Or.3Ab.5Q. On these assumptions the plagioclase proper is calculated to be nearly $An_{52}\,Ab_{38}\,Or_{10}$. Since some of the residual alkali-felspar may crystallize in continuity with the outermost zone of the plagioclase, this formula may be regarded as allotting to the plagioclase the maximum possible amount of anorthite.

Phenocrysts of plagioclase, commonly 2 mm. or more in length and about a third of this in width, occur sparingly in the Whin Sill. Teall recorded them from three localities, and careful search generally discloses their presence in most exposures of the more rapidly cooled portions of the Sill. No phenocrysts have been found in the more slowly cooled millimetre-grained rocks of High Force and Cauldron Snout. On the other hand, they can always be detected in the dikes that have risen into the cooler rocks of the Coal Measures, well above the horizons of the Whin Sill itself.

Fig. 1, plate X, illustrates from the Hett dike a perfectly limpid glomeroporphyritic aggregate of highly calcic plagioclase free from inclusions. More commonly the phenocrysts have irregularly rounded forms and are deeply penetrated by zones of streaky inclusions. Such a phenocryst from the Wackerfield dike has already been figured (**15**, pl. VIII, fig. 3). The Hett aggregates are mainly An_{90}, but the periphery is sharply zoned against the normal rock. A thin film of about An_{80} appears first and rapidly passes into a broader zone that ranges from An_{50} to An_{30}. The interiors of the crystals show ghosts of oscillating zoning representing the vicissitudes of their early magmatic history. A similar phenocryst in the Butterby dike gave An_{90} for the body of the felspar, and An_{50} for the outer rim, the latter passing into An_{80} on the inside and An_{25} on the outside. A section of the Ludworth dike revealed a phenocryst with strings of bleb-like inclusions of pyroxene and ores parallel to the periphery. Vague internal zoning is here exhibited against the inclusions. The Wackerfield example more closely resembles the corroded and dislocated phenocrysts of the Whin Sill. Here the inclusions are more abundant and consist of the minerals of the normal rock with, however, only a very little felspar. Most of the felspathic material of the invading streaks of magma seems to have reacted with the host to form a less calcic felspar.

The mechanism by means of which the phenocrysts were channelled by the magma is by no means clear, but the evidence is conclusive that the phenocrysts were not in equilibrium with the magma that consolidated as the rocks under investigation. We have here, in fact, a practical demonstration of a case of reaction theoretically discussed by Bowen:[1] that of adding crystals of $An_{90}Ab_{10}$ to an $An_{50}Ab_{50}$ liquid at the same

---

[1] N. L. Bowen, Journ. Geol. Chicago, 1922, suppl. to vol. 30, pp. 524–528.

temperature. Along the margins of the suspended inclusions and through a system of channels roughly concentric with the margins, reaction takes place with increase of volume, thus leading ultimately to the complete disintegration of the inclusion, and the gradual 'making over' of the whole of its material to the plagioclase with which the magma is successively in equilibrium.

The abnormal composition and the reaction phenomena imply that the phenocrysts must have crystallized within a magma of such composition that the plagioclase could begin at An_{90}. That is to say, the Whin Sill magma, in which plagioclase begins at about An_{70}, is itself a product of a deep-seated partial differentiation from a more cafemic parental magma. Of the mineral aggregates which crystallized from the latter only those which were lighter than the residual magma succeeded in remaining with it when the act of injection took place. Continuous reaction and mechanical disintegration proceeding before, during, and after the act of injection almost destroyed the evidence of the former existence of these felspathic aggregates, but here and there a few scattered remnants still remained when the magma finally consolidated. In accordance with this hypothesis the phenocrysts are least rare where the cooling was most rapidly accomplished.

Pyroxenes.—Taking the rocks as a whole, both rhombic and monoclinic pyroxenes occur, and two varieties of the latter may generally be distinguished. In some specimens, however, especially in the north, the rhombic pyroxene is rare and very much altered, and it may even fail altogether to appear. Thus, in an account of the petrology of the northern section of the Whin Sill by Dr. H. H. Thomas (**23**, p. 110), rhombic pyroxene is not recorded, though it was found in a section from Belford by Sir John Flett.[1] Describing the northern dikes Thomas states that 'enstatite appears to have been an original constituent' (**23**, p. 122). In the south the mineral is far more abundant, especially in the Hett system of dikes and in the Whin Sill of the Upper Tees and Pennine Escarpment. Teall, however, did not detect it in his analysed specimen from Cauldron Snout (**4**, p. 654).

Where it is well developed the rhombic pyroxene is pale grey-green and slightly pleochroic. It builds stout prismatic crystals with the terminations generally frayed as a result of marginal alteration to serpentine or fibrous amphibole. Similar internal alteration develops a patchy fibrous structure parallel to the length and variegated with clots of iron-ore. Measurements of the refractive indices by immersion

---

[1] J. S. Flett, Quart. Journ. Geol. Soc. London, 1901, vol. 64, p. 295.

show a range from 1·67 to 1·71, and as the sign is usually negative the mineral may be referred to as hypersthene, with the proviso that it is very near to, and may sometimes be, enstatite. The probable range of composition is indicated in fig. 2 by the region marked *H*.

Hypersthene, where present, appears to have begun to crystallize about the same time as plagioclase or in some cases a little later. It sometimes acts as nuclei around which plates or granular aggregates of the monoclinic pyroxenes have grown. Occasionally strips of a monoclinic pyroxene may be found in the hypersthene, as recorded by Teall (**4**, p. 652). Vogt ascribes this to 'unmixing' in the solid phase.[1] Apart from the production of this perthitic structure the hypersthene and monoclinic pyroxenes have crystallized successively in accordance with Roozeboom's Type IV.

The monoclinic pyroxenes occur as (*a*) elongated narrow prisms, faintly green or colourless and generally centrally twinned; and as (*b*) more or less irregular plates and aggregates of differently orientated grains, having grey-green to pale brown tints, purple being rarely suggested. The second of these is the 'dominant pyroxene' of Teall (**4**, p. 646). Wherever the relations are clear (*b*) is seen to have crystallized later than (*a*), but in some of the rocks as a result of alteration no clear distinction can be drawn between the two types. It is noteworthy that (*a*) is most conspicuous in the north in rocks that are poor in hypersthene (e. g. Holy Island and Beadnell dikes and the Whin Sill of Bamburgh, the Islestone, and Belford).

Both types are hypersthene-augites, (*a*) being nearly uniaxial, as recorded by Wahl,[2] in his classic paper on these minerals, and later by Flett[3] and Miss Heslop (**12**); while (*b*) has a larger optical axial angle, 2V generally approaching 50°.

In the coarse veins of Cauldron Snout, High Force quarry, and Tyne Head only one pyroxene is present and its optical characters agree closely with those of (*b*). Teall's analyses of the pyroxenes from the medium rock of Cauldron Snout and from the pegmatitic veins of Tyne Head show that chemically they are also closely akin. The analyses are reproduced below, together with later analyses of similar pyroxenes from similar rocks of other localities. In each case the molecular proportions of the metasilicates are stated as percentages of their sum in the table on p. 507.

[1] J. H. L. Vogt, Journ. Geol. Chicago, 1921, vol. 29, p. 519.

[2] W. Wahl, Tschermaks Min. Petr. Mitt., 1907, vol. 26, pp. 1–131.

[3] J. S. Flett, Quart. Journ. Geol. Soc. London, 1908, vol. 64, p. 295.

Analyses of Pyroxenes from Rocks of the Whin Sill type.

	I.	II.	III.	IV.
SiO_2	49·03	48·41	50·02	50·26
Al_2O_3	5·46	4·05	5·61	2·10
Fe_2O_3	n.s.d.	2·36	15·61	none
FeO	15·57	15·08	n.s.d.	18·20
MnO	0·22	0·37	trace	0·35
MgO	11·66	12·14	12·01	13·30
CaO	15·34	15·98	14·84	15·56
Alks.	1·24	n.d	0·96	—
H_2O	0·81	1·19	0·76	—
	99·33	99·58	99·81	100·57*

* Includes TiO_2 = 0·80.

I. From the Whin Sill, Cauldron Snout, Upper Teesdale. J. J. H. Teall, analyst (4, p. 648).

II. From a pegmatitic vein in the Whin Sill, above Tyne Head. J. J. H. Teall, analyst (4, p. 648 .

III. From a dike of augite-diorite,[1] Seven Pagodas, Chingelput district, South India. T. H. Holland, analyst (Quart. Journ. Geol. Soc. London, 1897, vol. 53, p. 407).

IV. From the Goose Creek diabase[1] sill, Virginia, U.S.A. E. V. Shannon, analyst (Proc. U.S. Nat. Mus., 1924, vol. 66, art. 2, p. 11).

In order to represent graphically the relations of this pyroxene to the more magnesian pyroxenes and to the rocks containing them, the triangular diagram fig. 2 was constructed, following a method devised by Dr. B. Asklund,[2] and utilizing the data collected by him. The curved line encloses an area the points within which represent the metasilicate proportions (femic $CaSiO_3$, $MgSiO_3$, and $FeSiO_3$ of the norm) of dolerites, gabbros, and norites which contain two kinds of pyroxene. Rocks represented by points outside the curve contain only one kind of pyroxene.

The femic metasilicate proportions calculated from analyses of the Whin Sill and related dikes (see pp. 513 and 530) are plotted in the diagram, and, as would be expected, they fall within the area of rocks with two pyroxenes. The analysed pyroxenes fall just outside the curve in the region *B*, in accordance with their relatively lower content of $MgSiO_3$. The earlier pyroxenes must therefore be magnesia-rich varieties, and the evidence of the rocks indicates that these include hypersthene near *H* and a nearly uniaxial hypersthene-augite near *A*. Asklund has shown that

---

[1] The parent rocks of III and IV are quartz-dolerites, like the Whin Sill, but of coarser grain.

[2] B. Asklund, Sveriges Geol. Undersökning, 1925, Årsbok 17 (for 1923), no. 6 (= Ser. C, Avhand. och Uppsat., no. 325), p. 77 and fig. 20, p. 78 and fig. 21.

the compositions of the uniaxial clinopyroxenes are represented by the line *OO*. This line separates a field on the diopside side with the optic axial plane parallel to (010), from a field on the clinohypersthene side with the optic axial plane normal to (010). Our pyroxenes of the (*a*) type are known to fall in both fields and their compositions must therefore lie in or near the region *A*.

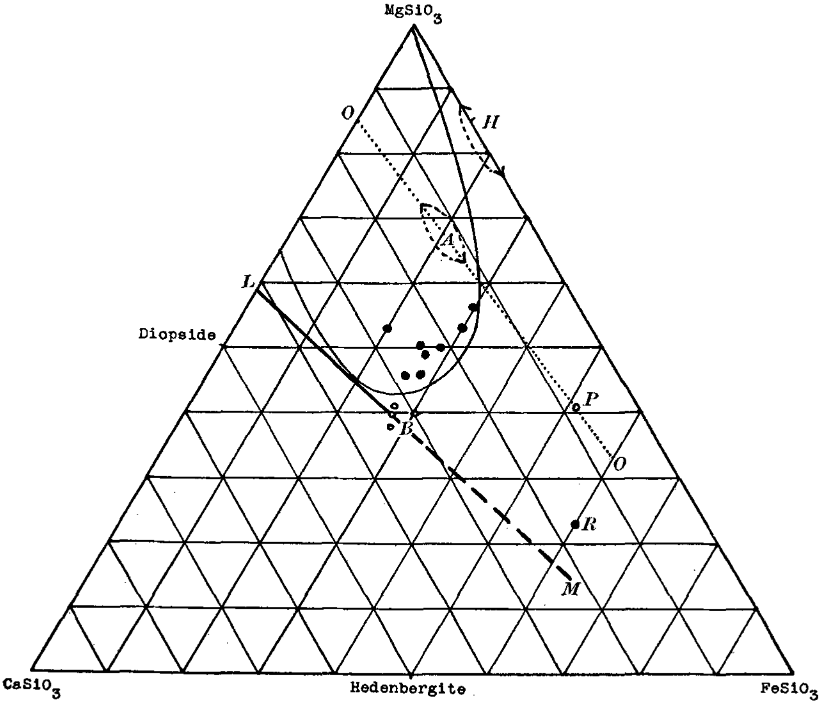


FIG. 2. Diagram to illustrate the chemical relations between rocks and their component pyroxenes.

Bowen's well-known work on the system clinoenstatite–diopside shows that it belongs to Roozeboom's Type III, the liquidus having a minimum at about 82 per cent. diopside (*L* in fig. 2). It is probable that the depression in the liquidus surface of the ternary metasilicate system of fig. 2 dips from *L* towards a point near the $FeSiO_3$ corner. The Tyne Head pyroxene cannot be far from the bottom of the groove, since it is optically uniform throughout, shows no trace of zoning, and has crystallized from the final residue of the Whin Sill magma. The depression of the liquidus surface may therefore be provisionally represented by a line such as *LM*.

Femic Metasilicate Proportions.

(Plotted in fig. 2.)

Rocks and Pyroxenes.	$CaSiO_3$.	$MgSiO_3$.	$FeSiO_3$.
Whin Sill:			
Cauldron Snout	28	46	26
Borcovicus	22	50	28
Rotherhope	26	46	28
Hilton	24	49	27
Dikes:			
Holy Island	24	50	26
Elsdon	27	53	20
Hett	14	56	30
Wackerfield	17	53	30
Pyroxenes:			
I	35	37	28
II	33	40	27
III	32	41	27
IV	30	40	40

On this interpretation the pyroxenes constitute a discontinuous reaction series. Hypersthene *H* appears first, followed by hypersthene-augite *A*, which in turn is followed by the less magnesian pyroxene *B*. We do not yet understand how it is that in some of the rocks *H* is the dominant magnesian pyroxene, whereas in others its place is largely taken by *A*; but it is clear that the two are mutually complementary, and that their separation from the magma enriched the latter in CaO and FeO.

The boundary curve *LM* cannot be the individualization boundary of a system of Roozeboom's Type V, for, if it were, the composition *B* would be represented by two pyroxenes respectively more and less calcic. Since in all the rocks examined the course of crystallization leads to a single pyroxene (*b*), it follows that the natural system hypersthene-augite–diopside-hedenbergite belongs to Type III, like the artificial system clinoenstatite–diopside. The small quantities of $AlAlO_3$ and $FeFeO_3$ which enter into the natural minerals do not appear to affect in any significant way the relations deduced from the metasilicates alone.[1]

Note on the Pyroxenes of Inninmorite.—If the above interpretation is correct, it raises the interesting question whether the partial crystallization of a basaltic magma could generate a residual magma from which

---

[1] R. W. G. Wyckoff, H. E. Merwin, and H. S. Washington, Amer. Journ. Sci., 1925, ser. 5, vol. 10, p. 393. See also in this paper the results of chemical and X-ray analyses of an iron-rich hypersthene-augite from one of the Deccan plateau basalts.

a rock like the inninmorite of Mull[1] could be formed. In this rock (*R* in fig. 2) the first-formed pyroxene is a uniaxial augite (*P* in fig. 2) that has been thoroughly investigated by Mr. A. F. Hallimond.[2] The later groundmass-augite (when developed) must be somewhere near *M* in fig. 2; that is to say, near the suggested groove in the liquidus surface. There is no evidence of the simultaneous crystallization of *P* and *M*, so that the system cannot be an example of Type V. Indeed the rounded forms of the uniaxial pyroxene *P* suggest that it is the first member of a discontinuous reaction series. The inninmorite magma has thus behaved like a basaltic magma diluted with a magma of, say, granophyre composition, rather than as a residual magma produced in part by the crystallization of its pyroxenes along *LM*. A similar hypothesis is worthy of consideration in explanation of the puzzling features of the rocks of the 'differentiation column' of the Glen More Ring Dike,[3] and although the matter cannot be pursued here, further evidence bearing on the kind of hypothesis suggested is presented on page 511.

4. Mineral Composition of the Whin Sill.

A series of micrometric analyses of sections of the Whin Sill from widely different localities (all of medium grain), carried out with a Shand's micrometer,[4] gave the results recorded in the following table. The localities are arranged in order along the outcrop from north to south. The 'pyroxenes' of this and later tables include all three types of pyroxene together with brown hornblende and green alteration products developed in situ. The latter, taken alone, generally amount to 2 or 3 per cent., but in places they rise to 8 or 9 per cent. Biotite is not sufficiently abundant to affect the results. In measuring the plagioclase special care was taken to avoid the inclusion of quartz, micropegmatite (where present), and interstitial biscuit-tinted or chlorite-stained felsitic matter.

Micrometric Measurements of the Whin Sill.

	Localities.	Pyroxenes (P).	Plagioclase (F).	F/(P + F).
502.	Belford	30·2 ...	52·3 ...	63 %
512.	Islestone, Bamburgh	33·7 ...	49·8 ...	60
517.	Snook Point ...	30·0 ...	55·5 ...	65

---

[1] Mem. Geol. Survey Scotland, Tertiary and post-Tertiary geology of Mull, 1924. Analysis V of Table III, p. 19, fig. 48 B, p. 283.

[2] Ibid., Analysis I of Table IX, p. 34.

[3] Ibid., pp. 28–29 and pp. 320 et seq.

[4] Except for the Greenhead and Kirkwhelpington specimens which were measured at the Imperial College in 1921 (**15**, p. 449).

	Localities.	Pyroxenes (P).	Plagioclase (F).	F/(P + F).
519.	Longhaughton	34·6	49·3	58 %
—	Kirkwhelpington	33·1	53·7	62
529.	Chollerton	35·3	51·2	59
532.	Hot Bank	31·4	51·8	62
—	Greenhead	39·8	48·9	55
555.	High Cup Gill	32·6	51·4	61
551.	Scordale Beck	37·8	48·3	56
	Average by volume	33·8	51·2	60
	Average by weight	35·8	46·3	56

Another series of measurements on sections from different levels in the same vertical exposure gave the following results (by volume):

Micrometric Measurements of the Whin Sill.

	Localities.	Pyroxenes (P).	Plagioclase (F).	F/(P + F).
High Cup Gill:				
553.	2 feet from top of Sill	37·5	50·6	57 %
555.	Middle of Sill	32·6	51·4	61
556.	1 foot from bottom	36·3	50·1	58
Scordale Beck near Hilton lead mines:				
552.	Middle of Sill	31·6	52·3	62
551.	6 feet from bottom	37·8	48·3	56
549.	2 inches from bottom	38·7	49·0	56

These figures show that the middle of the sill tends to be richer in plagioclase and poorer in pyroxenes than the margins. A series of measurements of the black ores reveals an apparent increase towards the base of the sill. It is difficult, however, to decide if this variation is genuine, because opaque minerals must inevitably be over-estimated by micrometric analysis. The intercept measured is necessarily greater than the average for the thickness of the section, except where the edges are normal to the section. This persistent source of error therefore increases with the number of edges, that is, with the number of individuals. In fine-grained specimens the black ores are small and ragged, and skeletal forms are common; whereas in those of medium grain the ore individuals are larger, more continuous, and less numerous. Estimates of the ores therefore increase inversely with the grain size, and measurements may give results that, judged by the chemical analyses, are too high by 50 per cent. or more. This source of error also affects the pyroxenes and felspars in a complementary way, but as these minerals are more abundant and are themselves subject to boundary uncertainties of other kinds its relative importance is not serious.

The results as a whole reveal a range of variation that is remarkably narrow, and such slight diversity as does occur is almost as marked within the limits of a single exposure as in the whole extent of the sill.

The pegmatite veins are less difficult to measure, though the labour involved is more protracted on account of the coarseness of grain. Mr. S. Tomkeieff is making a special study of the pegmatoid facies of the Whin Sill and he has kindly permitted us to record the following hitherto unpublished analyses (percentages by volume):

Micrometric Analyses of the Whin Sill. (By S. Tomkeieff.)

Minerals.	Crook Boring.			High Force Quarry.	
Pyroxene (P)	20·00	15·55	25·19	13·34	25·37
Hornblende (H)	11·30	9·63	10·71	11·52	7·93
Plagioclase (F)	41·30	41·20	41·55	41·22	41·13
Micropegmatite	15·90	25·13	12·09	22·19	14·27
Quartz	1·90	3·60	2·91	2·60	2·92
Opaque Ores...	9·60	4·91	7·55	9·13	8·38
F/(P+H+F)	57	62	54	63	55 %

It is noteworthy that both the plagioclase and the ferromagnesian minerals are less abundant than in the normal rock of the Whin Sill. The average ratio of felspar to the sum of felspar and ferromagnesian minerals is, however, not very different from that found for the normal rock, being 58 against 60. This result is important because in the consolidation of a plagioclase-pyroxene melt one would expect the plagioclase-ratio to increase in the melt as crystallization proceeds instead of decreasing. Micropegmatite, however, has very definitely increased, suggesting that as cooling progressed the constituents of orthoclase and quartz tended to form with the constituents of albite a mixture akin to a ternary eutectic, and that the albite required to maintain this composition (as a quasi-independent system within the residual magma) was no longer available for reaction with the plagioclase to the same extent as it would have been in a pure felspar melt. Otherwise it is difficult to understand why the increase in micropegmatite should not have been accompanied by an increased amount of plagioclase having a markedly lower anorthite content. The fact that the plagioclase of the later coarse veins is practically identical with the plagioclase of the previously crystallized surrounding rock implies the effectual transference of some of the potential albite from the system concerned in the crystallization of plagioclase to the system concerned in the later crystallization of alkali-felspar. The same conclusion can be deduced from the mineral composition and chemical analyses of the closely similar diabase and diabase-pegmatite of Goose Creek.[1] The detailed descriptions of Shannon show that the relations between the two types of rock are parallel in every respect to those between the Whin Sill and its pegmatitic veins.

The conception of such a retention of the constituents of albite by those of quartz and orthoclase prior to crystallization has important bearings on the common association of rocks of basaltic and granophyric composition in regions underlain by sial. It does not imply that an extensive granophyre-magma could separate from a parent basaltic magma —the volume relations and the absence of granophyric rocks from oceanic islands forbid that deduction—but it does suggest that if the two magmas existed side by side, or were even mixed together at not too high temperatures, they would still to a certain extent preserve their individualities, and either separate out by crystallization or otherwise, or give rise to a hybrid series of rocks. As already pointed out, the inninmorite and related rocks of Mull seem to be abnormal types produced from just such a mixture of originally independent magmas.

5. Chemical Composition of the Whin Sill.

In selecting a sample of the Whin Sill for analysis, preference was given to a specimen from Scordale Beck (near Hilton lead mines) because of the finding of a pebble of quartz-dolerite of the Whin Sill type in the Upper Brockram not far to the west, and the desirability of comparing an analysis of a fragment of this pebble with one of the Whin Sill from the immediate neighbourhood (see p. 530). The analysed specimen (551) was taken from a level 6 feet above the base of the Sill and is of fine-grained texture. Apart from the alteration to bastite of the original hypersthene (very little of which remains), the rock is quite fresh and is almost devoid of the biscuit-coloured mesostasis, such interstitial minerals as occur (other than the later pyroxene) being quartz and alkali-felspar. No micropegmatite has been detected. Some of the plates of later augite have a faint purple tint, like that of the corresponding mineral in the pebble. The percentages of plagioclase and pyroxenes by volume are given on p. 509.

The results of the analysis are tabulated below together with a re-calculation in terms of the standard compounds of the norm.

---

[1] E. V. Shannon, Proc. U.S. Nat. Mus., 1924, vol. 66, art. 2.

Chemical Composition of the Whin Sill (551), Scordale Beck, Westmorland.

	Percentages.	Molecular Proportions.
SiO_2	51·04	0·850
Al_2O_3 ...	13·69	0·134
Fe_2O_3 ...	2·97	0·019
FeO	9·12	0·127
MgO	5·75	0·143
CaO	9·46	0·169
Na_2O	2·27	0·037
K_2O	1·01	0·011
H_2O (+110° C.)	1·48	—
H_2O (−110° C.)	0·37	—
CO_2	0·29	0·007
TiO_2	2·22	0·028
ZrO_2	none	—
P_2O_5	0·30	0·002
Cl	trace	—
S	0·12	0·004
Cr_2O_3	none	—
V_2O_3	0·06	0.0004
NiO	none	—
MnO	0·22	0·003
SrO	trace	—
BaO	0·03	0.0002
Li_2O	trace	—
	100·40	
Less O for S ...	0·04	
	100·36	

Specific gravity = 2·95.

Norm.			
Quartz			5·74
Orthoclase			6·12
Albite			19·40
Anorthite			24·03
Diopside	$CaSiO_3$	8·08	15·86
	$MgSiO_3$	4·46	
	$FeSiO_3$	3·32	
Hypersthene	$MgSiO_3$	9·90	17·26
	$FeSiO_3$	7·36	
Magnetite			4·40
Ilmenite			4·25
Pyrite			0·24
Apatite			0·67
Calcite			0·70
			98·67
Water			1·85
			100·52

Calculated Mineral Composition.

Quartz	6·76
Alkali Felspars, $Ab_{60}Or_{40}$ ...	4·45
Plagioclase, $An_{48}Ab_{42}Or_{10}$ ...	40·40
Pyroxenes	36·76
Ores	8·90
Apatite	0·67
Calcite	0·70
	98·64

A closer approach to the mode can be made by adding to the normative pyroxene an amount of Al_2O_3 equivalent to 5 per cent. (see p. 505) and assuming that the plagioclase contains 10 per cent. of orthoclase, and that the remaining orthoclase has crystallized with albite in the proportion $Ab_{60}Or_{40}$ either in micropegmatite or as an independent felspar.[1] The first of these operations decreases the amount of anorthite, increases the $CaSiO_3$ in the pyroxene,[2] and increases the normative quartz. The third decreases the amount of albite in the plagioclase. The combined

---

[1] More strictly this should be about $An_1Ab_{58}Or_{41}$. See J. H. L. Vogt, The physical chemistry of the magmatic differentiation of igneous rocks. II. On the Felspar Diagram Or : Ab : An. Skrifter Norske Vidensk. Akad. I. Mat.-nat. Kl., Oslo, 1926, no. 4, pp. 16–17.

[2] The difference does not materially affect the plotted positions of the rocks in fig. 2.

results increase the calculated amount of pyroxene and give a probable allocation to the felspar compounds, thus providing figures that may be referred to as the ‘calculated mineral composition’.

The analysis is that of a typical oversaturated dolerite. It is repeated below for comparison with the analyses already recorded by Teall and others of samples of the Whin Sill from other localities. The figures clearly reveal a remarkable uniformity in the bulk composition of the rock from point to point. The somewhat low magnesia of B is in agreement with Teall's statement that the rock analysed appeared to be free from hypersthene.

Chemical Analyses of the Whin Sill.

	A.	B.	C.	D.	E.
SiO_2	51.04	51.22	50·71	50·46	49·54
Al_2O_3	13·69	14·06	14·78	13·89	16·64
Fe_2O_3	2·97	4·32	3·52	3·69	n.s.d.
FeO	9·12	9·03	8·95	9·02	11·44
MgO	5·75	4·42	5·90	5·03	5·51
CaO	9·46	8·33	8·21	8·81	9·00
Na_2O	2·27	2·55	2·76	2·85	2·33
K_2O	1·01	1·25	1·39	1·33	0·97
H_2O+	1.48	1·28	1·78	1·95	0·47
H_2O-	0·37				
CO_2	0·29	0·19	0·25	0·19	0·16
TiO_2	2·22	2·42	1·92	2·26	2·84
P_2O_5	0·30	0·25	n.d.	0·37	0·28
MnO	0·22	0·16	0·31	0·22	0·20
S	0·12	0·26	n.d.	n.d.	—
	100·36*	99·74	100·48	100.07	99·38
Sp. gr.	2·95	2·98	2·94	2.853	2·900

* Including $V_2O_3 = 0·06$; $BaO = 0·03$.

A. Scordale Beck, near Hilton lead mines, Westmorland. H. F. Harwood, analyst.

B. Cauldron Snout, Durham. J. J. H. Teall, analyst (4, p. 654).

C. Crags near Borcovicus, Northumberland. J. J. H. Teall, analyst (4, p. 654).

D. Rotherhope, near Alston, Cumberland. A. M. Finlayson, analyst (10, p. 304).

E. Snook Point, north of Dunstanburgh, Northumberland. J. A. Smythe, analyst (14, p. 250).

The high alumina of E corresponds with the high plagioclase content found by micrometric analysis on one of Dr. Smythe's specimens from the same locality (p. 508). Comparison of the magma-type with its representatives elsewhere is deferred to a later part of this paper.

6. THE HOLY ISLAND DIKE-ECHELON.

This series of dikes begins in the Tweed valley half a mile below Coldstream, and can be traced beyond the coast as far as a steep-sided sunken reef ominously known as Steel End, which lies half a mile east of the Goldstone Rock. The latter is an almost submerged continuation of the Holy Island dike about two miles from the land. The chief members of the echelon from west to east are the Cornhill, Bowsden and Lickar Dean, Kentstone, Kyloe Cottage, and Holy Island dikes. From Lickar Dean eastwards they have recently been described by the Geological Survey (**23**, pp. 121–124). The Cornhill dike has been merely mentioned by Lebour (**5**, p. 91). The Holy Island dike varies in width from 10 feet on the mainland to over 200 feet at the Castle on the Island.

Tectonics.—Regarded as a fissure system the echelon series of dikes resembles the sequence of marginal crevasses developed on one side of a glacier. These run downstream, at an angle from the central region of maximum flow towards the lateral belt of minimum flow, and are a consequence of the tension resulting from the pull of the relatively mobile interior on the more sluggish marginal belt. The great north-south Holburn anticline, with the down-faulted Lowick-Hetton syncline running parallel on the west, indicates powerful east-west compression between the Cheviots and the coast. The disturbance becomes much less severe as the belt of dikes is approached, and we might therefore interpret the dike-fissures as a consequence of easterly rock-flowage from the Cheviot region towards the sea, the region north of the dikes being relatively inert. The main folding, however, must have preceded the injection of the dikes, because the Kentstone dike lies across the nose of the anticline where it is pitching to the north, and the dike itself shows no sign of having been folded.

The emplacement of the Whin Sill also points to the same sequence of events. The eastern limb of the anticline, which is asymmetrical, slopes gently seaward, and here the Whin Sill reaches a thickness of 120 feet. The western flank dips steeply, and on this side the sill is known with certainty in one locality only (**23**, p. 118); there it dips west with the Carboniferous strata at 45° and is reduced in thickness to 10 or 12 feet. Farther to the west the sill is absent from the Lowick-Hetton syncline. Discussing this the Survey geologists write, 'In view of the general tendency of sills to be concordant with the bedding, this contrast between the two limbs of the fold would be very strange if the folding were later than the consolidation—the sill would be expected in this case to have approximately the same thickness on both sides of the axis', and they proceed to deduce that the Holburn anticline 'was already in existence at the time when the Whin Sill was injected' (**23**, pp. 120–121).

The field relations of the Whin Sill and of the dikes are therefore consistent with the view that fissuring and magmatic injection were both made possible by differential easterly movements which followed the main puckering of the folded belt in front of the Cheviots.

Petrology.—We have little to add to the brief account by Thomas, who describes the Holy Island dike as a 'compact dark grey quartz-dolerite that closely resembles the Whin Sill both in texture and mineralogical composition. It contains the same two generations of monoclinic pyroxene, the earlier, as in the case of the Whin Sill, being an enstatite-augite with marked prismatic habit' (**23**, p. 121). In our analysed specimen (558) no fresh hypersthene was found, but some of the decomposition products may possibly represent it. Hornblende, followed by chlorite, has grown on the pyroxene in places. The felspars are turbid, suggesting incipient albitization. A section of the Kentstone dike (559) is finer grained, and differs in containing a noticeable amount of patchy mesostasis in which interlacing strings of black globulites have developed. The titanomagnetite is in small irregular grains and skeletons, not nearly so well individualized as in the Holy Island specimen. Micrometric analyses of these two sections gave the following results (percentages by volume):—

Micrometric Measurements of Dikes of the Holy Island Echelon.

	Dike.	Pyroxenes (P).	Plagioclase (F).	F/(P + F).
558.	Holy Island	36·5	51·0	58 %
559.	Kentstone	29·7	48·6	62

Chemical Composition.—The analysis which follows of the Holy Island dike shows that the latter is practically identical with the Whin Sill in chemical composition. Soda is higher and lime lower than in the other dikes analysed, but the figures do not fall outside the range for the Whin Sill. The relatively high soda is probably a result of the slight albitization which some of the felspars have suffered.

Chemical Composition of the Holy Island Dike (558).

	Percentages.	Molecular Proportions.	Norm.	
SiO_2	50·77	0·845	Quartz	3·58
Al_2O_3	13·64	0·134	Orthoclase	7·23
Fe_2O_3	3·17	0·020	Albite	24·12

	Percentages.	Molecular Proportions.
FeO	8·87	0·123
MgO	5·66	0·140
CaO	8·44	0·150
Na_2O	2·83	0·046
K_2O	1·19	0·013
H_2O (+110° C.)	1·61	—
H_2O (−110° C.)	0·75	—
CO_2	0·02	0·0005
TiO_2	2·49	0·031
ZrO_2	none	—
P_2O_5	0·28	0·002
Cl	trace	—
F	none	—
S	0·05	0·002
Cr_2O_3	trace	—
V_2O_3	0·05	0·0003
NiO	none	—
MnO	0·15	0·002
SrO	none	—
BaO	0·03	0·0002
Li_2O	trace	—
	100·00	
Less O for S ...	0·02	
	99·98	

Specific gravity = 2·97.

Norm.			
Anorthite			20·94
Diopside	$CaSiO_3$	7·86	15·39
	$MgSiO_3$	4·47	
	$FeSiO_3$	3·06	
Hypersthene	$MgSiO_3$	9·59	16·16
	$FeSiO_3$	6·57	
Magnetite			4·63
Ilmenite			4·71
Pyrite			0·12
Apatite			0·67
Calcite			0·05
			97·60
Water			2·36
			99·96

Calculated Mineral Composition.	
Quartz	4·66
Alkali Felspars, $Or_{40}Ab_{60}$ ...	6·83
Plagioclase, $An_{40}Ab_{50}Or_{10}$ ...	40·48
Pyroxenes	35·44
Ores	9·46
Apatite	0·67
Calcite	0·05
	97·59

7. THE HIGH GREEN DIKE-ECHELON.

This system begins west of the North Tyne, near the Border, with the Lewisburn dike which has been well described by Clough and Teall (**8**, p. 22). In the railway cutting east of the North Tyne its thickness is 105 feet; at The Cross it is 250 feet; but beyond this point it becomes thinner. The High Green dike made familiar by Teall (**3**, pp. 239–242) is 50 feet thick where it crosses the Tarret Burn, and is considered to be a continuation of the Lewisburn dike. A mile and a quarter to the north the dike system is continued by the northern High Green dike, 20 to 30 feet thick in the Tarret Burn (**6**, p. 99). This continues eastward towards Redesdale as the Trough End dike. On the other side of the Rede, near Otterburn, there are three little dikes, representing at least one farther step up the echelon. North of Elsdon there are three dikes, the southernmost being of minor importance. The main Elsdon dike extends across the valleys of the Elsdon and Grasslees Burns and where exposed in the burn sides its thickness is seen to range from 145 to 200 feet. The specimen (572) of which the analysis follows was collected from the Grasslees Burn. Half a mile north the echelon is continued by the North Elsdon dike, here 160 feet thick. Farther on there is another step north (or possibly two) where the Rothbury dikes appear from Tosson to Tumbleton. Next follows the Flamborough dike, 80 feet thick where it is quarried, in a line with the Hampeth dike which reaches a thickness of 150 feet. The little Shilbottle and Bilton dikes depart from the usual trend, but they are well in line with the axis of the echelon which reaches the coast in the Boulmer dike north of Alnmouth.

Between Boulmer and Holy Island two other dikes appear on the coast: one at Howick, just south of the Whin Sill at Cullernose Point, and the other at Beadnell (**23**, p. 122).

Tectonics.—Interpreting the fissures of the High Green echelon in the same way as those of the Holy Island echelon, that is, regarding them as analogous in their mode of formation to the marginal crevasses of a glacier, we find that they imply a region of differential easterly rock-flowage to the north. Corresponding to the Holburn disturbance is the very similar Swindon fault with its accompanying evidence of powerful compression, and the continuation of this dislocation NNE. from Rothbury. From the neighbourhood of Rothbury to the Elsdon Burn a belt of intense folding runs nearly parallel to the dikes and the injection of the latter could not therefore have been accomplished at the same time as the folding. The relations of the faults of this district to the folds and the dikes suggest that the folds came first. We thus reach the conclusion that after the folding the region including the Cheviot massif was moved bodily towards the east relatively to the bordering echeloned belts. Corresponding to the longitudinal crevasses of a glacier, we find straight in front of the Cheviots the Beadnell and Howick dikes. The Beadnell dike shows no signs of having been tilted with the strata which it penetrates, so that throughout the region the evidence points consistently to the conclusion that the intrusions followed the main folding. The recent work of the Survey has shown that some of the east-west tear faults also preceded the Whin Sill (**21**). Others, however, are of later date.

Petrology.—Teall's description of the High Green dikes (**3**, p. **241**) and of the Lewisburn dike (**8**, p. 22), and our own examination of these and of the Trough End, Elsdon, Boulmer, and Beadnell dikes, show that as a whole the rocks are of the Whin Sill type. The grain size in the thicker dikes tends to be distinctly higher than that of the neighbouring Whin Sill, but it does not reach the millimetre grain of the coarser rocks south of the Tyne in which the pegmatitic veins occur. The relatively slow cooling thus suggested, as well as the great thickness of many of the dikes, is probably to be correlated with the fact that from the Border to Flamborough the dikes are exposed in rocks that lie stratigraphically well below the Whin Sill. Marginal specimens carry the grain size down to the usual limits, and it is noteworthy that phenocrysts of highly calcic plagioclase (corroded type with inclusions) occur in the finer parts of the Lewisburn dike, and were found by Teall in a specimen of the northern High Green rock which contains 'a very small quantity of a pale brown isotropic glass'.

The Beadnell, Lewisburn, and High Green dikes contain only traces of hypersthene, and this is thoroughly altered in the slides examined. Some of the others contain clear, grey to faintly brown hypersthene, more or less abundantly streaked and fringed with green and black alteration products. The analysed rock (572) from Grasslees Burn, near Elsdon, contains all three types of pyroxene, the sparse and altered hypersthene being sometimes enclosed within nearly uniaxial hypersthene-augite. The dominant final augite differs little in colour from the latter, and it has crystallized with marked ophitic relations to the plagioclase. Brown hornblende has grown in the pyroxenes, followed by chlorite, and traces of biotite can be detected between the ores and the interstitial felspar. The ores are mostly large irregular individuals, but there is a sprinkling of smaller grains and skeletal growths. They are more abundant in this rock than in any other of the north of England Whin Sill types, except possibly the St. Oswald's Chapel dike which is locally rich in ores (fig. 2, plate X).

The following micrometric analyses show the proportions of plagioclase and pyroxenes in some of the dikes of the High Green echelon, and in the Beadnell dike.

Micrometric Measurements of Dikes of the High Green Echelon.

	Dikes.	Pyroxenes (P).	Plagioclase (F).	F/(P + F).
536.	High Green...	33·8	50.6	59 %
530.	Trough End	37·1	51·4	57
572.	Elsdon ...	36·0	52·1	59
576.	North Elsdon	33·2	54·2	62
568.	Boulmer ...	34·5	49.7	59
560.	Beadnell ...	35·6	55·3	61

The dikes of this echelon are locally altered by hydrothermal processes to a far greater extent than the Whin Sill or the other dikes. Teall refers to the alteration of the High Green dikes (3, p. 240) and Thomas to the albitization of the Hampeth dike (**23**, p. 122). In a specimen of the Lewisburn dike from the Pot Burn (569) the felspars are reduced to albite or oligoclase and crowded with sericite flakes and secondary quartz. The pyroxenes are mainly represented by a green felt, probably of serpentinous nature, charged with blebs of a carbonate mineral. The titano-magnetite, however, remains unaffected. Amygdales of vermicular chlorite enclosing calcite are present, but they are not numerous. The alteration may be due to the upward passage through the rock of a residual fluid, rich in the constituents of alkali-felspars, silica, water, and carbon-dioxide, produced at greater depths by the normal crystallization of the magma. Sericite would then be developed by the interaction of orthoclase (in solution) with anorthite (in the plagioclase crystals):

$$H_2O + CO_2 + KAlSi_3O_8 + CaAl_2Si_2O_8 = KH_2Al_3Si_3O_{12} + 2SiO_2 + CaCO_3.$$

The essential change is one of sericitization, with albite produced as a by-product, rather than albitization of the kind characteristic of the spilitic suite.

Chemical Composition.—The analysed specimen (572) from the Grasslees Burn, a mile and a quarter NNE. of Elsdon, gives results of the usual Whin Sill type. A slight relative deficiency in magnesia is more than made good by the iron oxides, and corresponding with the unusually high proportion of ores ferric oxide here reaches its maximum among the analysed rocks, and titanium dioxide is exceeded only in the St. Oswald's Chapel dike. The analysis of the closely similar rock from High Green by J. E. Stead (**3**, p. 240) must now be set aside as valueless.

Chemical Composition of the Elsdon Dike (572).

	Percentages.	Molecular Proportions.	Norm.			
SiO_2	49·59	0·826	Quartz			7·88
Al_2O_3	13·66	0·134	Orthoclase			5·56
Fe_2O_3	5·29	0·033	Albite			19·40
FeO	7·90	0·110	Anorthite			24·28
MgO	5·09	0·126	Diopside	$CaSiO_3$	7·49	14·52
CaO	9·34	0·166		$MgSiO_3$	4·70	
Na_2O	2·27	0·037		$FeSiO_3$	2·33	
K_2O	0·91	0·010	Hypersthene	$MgSiO_3$	7·95	11·91
H_2O (+110° C.)	1·51	—		$FeSiO_3$	3·96	
H_2O (−110° C.)	1·13	—	Magnetite			7·64
CO_2	0·52	0·012	Ilmenite			4·86
TiO_2	2·59	0·032	Pyrite			0·10
ZrO_2	none	—	Apatite			0·23
P_2O_5	0·10	0·0007	Calcite			1·20
Cl	trace	—				97·58

	Percentages.	Molecular Proportions.
S	0·05	0·0015
Cr_2O_3	none	—
V_2O_3	0·05	0·0003
NiO	none	—
MnO	0·25	0·0035
SrO	trace	—
BaO	0·01	0·0001
Li_2O	trace	—
	100·26	
Less O for S ...	0·02	
	100·24	

Specific gravity = 3·01.

Norm.	
Water	2·64
	100·22

Calculated Mineral Composition.	
Quartz	8·66
Alkali-felspars. $Ab_{60}Or_{40}$ ...	3·00
Plagioclase, $An_{49}Ab_{41}Or_{10}$ ...	42·46
Pyroxenes	29·40
Ores	12·60
Apatite	0·23
Calcite	1·20
	97·55

8. The St. Oswald's Chapel Dike-Echelon.

The successive members of this series are the dikes of Haltwhistle, Haydon Bridge, St. Oswald's Chapel, Bavington, Bolam, Mitford, and Causey Park. The second and third of these were described by Lebour as the Brunton dike in the following words (**2**, p. 50; **5**, p. 89): 'The *Brunton Dyke*, known in West Allendale, near Whitfield, crosses the South Tyne first to the West of Haydon Bridge, then between that little town and Wharnley, and lastly to the East of the latter place; it crosses the North Tyne near Wall, is well exposed by St. Oswald's Chapel, near Brunton, and is last seen in the Bingfield Burn on the East side of the Watling Street'. The beginning of this description is probably carelessly worded, for Whitfield is five miles south of the point where the dike begins, and no dike has since been recorded or mapped from West Allendale, even on Lebour's own Geological Map of Northumberland. At the other end, in the neighbourhood of Bingfield, we are faced with the difficulty that there is no stream marked on the Six-inch map, or known to the local inhabitants, as the 'Bingfield Burn'. It is clear, however, from Teall's account of his visit to the 'Bingfield Burn' (**3**, p. 236) that the Redhouse Burn is intended.

Teall's own suite of specimens labelled 'Brunton dyke, near Bingfield', now in the Geological Department of the Durham Colleges, is identical in every detail with a suite collected from the Redhouse Burn exposure which is close to the Milestone on the Watling Street five miles from Corbridge. The rocks themselves, however, do not belong to the Brunton dike of Lebour, but to a tholeiite dike of very different character when seen under the microscope. Figs. 3 and 4 on plate X show the contrasted appearances in thin section of the St. Oswald's Chapel quartz-dolerite and the Bingfield tholeiite respectively. The latter has been adopted by the petrologists of the Geological Survey as the type-example of the 'Brunton type' of tholeiite,[1] and the name has already become familiar to British petrologists. As Brunton is only three miles away from the Redhouse Burn exposure, there can be no possible objection to retaining the term in its petrological application to a rock-type. The name, however, should no longer be used for the dikes described by Lebour. To avoid confusion, and with the approval of Dr. H. H. Thomas and Mr. E. B. Bailey, it is proposed that the dike behind St. Oswald's Chapel should henceforth be known as the 'St. Oswald's Chapel dike', and that the dike in Redhouse Burn should be known as the 'Bingfield dike'.

The rock of the Bingfield dike is the type-example of the Brunton type of tholeiite, which was described by Teall under the impression that it represented the end of the St. Oswald's Chapel dike, whereas *the rock of the St. Oswald's Chapel dike is a characteristic quartz-dolerite of the Whin Sill type.*

Micrometric analyses of typical specimens of these two dikes bring out effectively the contrast in mineral development between them. In the north of England tholeiites, as pointed out by Mockler (**25**, p. 245), 'the pyroxene exceeds or equals the plagioclase in proportion', whereas in the rocks of the Whin Sill type the plagioclase is always in excess. The results tabulated below are completely in accordance with this generalization.

Micrometric Measurements of the St. Oswald's Chapel and Bingfield Dikes.

Dikes.	Pyroxenes (P).	Felspars (F).	F/(P + F).
St. Oswald's Chapel:			
571. S. of Roman Wall	36·5	50·3	58 %
573. St. Oswald's Chapel	32·6	49·2	60
574. Errington	33·7	48·3	59
Average	34·3	49·6	59
Bingfield (Brunton type of tholeiite):			
367	30·3	33·7	53
368	38·7	28·6	43
369	32·3	29·6	48
— (by G. S. Mockler)	31·9	31·5	50
369 (by A. E. Phaup)	35·8	31·3	47
Average	33·8	30·9	48

---

[1] Mem. Geol. Survey Scotland, Mull, 1924, p. 372.

The Bingfield dike will be described (with a chemical analysis) in a subsequent paper on the tholeiite series of dikes.

Tectonics.—The St. Oswald's Chapel echelon is not so strikingly developed as those farther north, possibly because the little dikes in the Morpeth neighbourhood are neither well exposed nor deeply denuded. The arrangement of the fissures from the Haydon Bridge dike onwards implies a north-easterly drag of the country to the north-west relative to the region to the south-east. The disposition of the Haltwhistle dike, however, shows that here the drag to the east was relatively greater in the country to the south. The Burtree Ford disturbance, which is of the same type as the Lowick-Hetton and Swindon dislocations, but with the downthrow on the seaward side, begins between the Haltwhistle and Haydon Bridge dikes, and the block of country between this highly disturbed belt and the Pennine faults may well have reacted to the stresses differently from the country to the east. The first movements of the Burtree Ford dislocation almost certainly preceded the intrusion of the Whin Sill because the latter changes its horizon suddenly in crossing the fault.

Petrology.—The rock from behind St. Oswald's Chapel is a hypersthene-bearing variety. Sections of the more fine-grained specimens appear to be unusually rich in ores, and have conspicuous patches of dark grey-brown mesostasis. These contain nearly colourless acicular needles and frond-like growths of what is probably pyroxene, minute felspars, and twig-like aggregates of black globulites. Globulites are also very abundant between the felspars, and between felspars and chlorite-stained intersertal material. The proportions of pyroxenes and plagioclase are given in the preceding table. A specimen from near Errington is similar in its possession of mesostasis, but one from south of the line of the Roman Wall is more completely crystalline and contains more pyroxene. The Haydon Bridge dike shows exactly the same range of characters. A section of the Bavington dike is indistinguishable from one of the neighbouring Whin Sill, being practically free from mesostasis.

Chemical Composition.—The specimen (573) from behind St. Oswald's Chapel has the normal composition of the Whin Sill type. The high proportion of ores has already been mentioned; it is here reflected in the high ferric oxide, and in the high titanium dioxide, which reaches its maximum among the analysed rocks. The relatively low ferrous oxide is to be correlated with the comparatively low percentage of pyroxenes in the rock. Reference to the table on page 530 shows that titanium dioxide generally amounts to well over 2 per cent. in the Whin Sill type.

Here it is 2·63, whereas the corresponding figure for the Bingfield dike is only 1·14, the range for the north of England tholeiites being 0·8 to 1·4 per cent.

Chemical Analysis of the St. Oswald's Chapel Dike (573).

	Percentages.	Molecular Proportions.
SiO_2	51·13	0·851
Al_2O_3	13·96	0·137
Fe_2O_3	4·76	0·030
FeO	6·88	0·096
MgO	5·44	0·135
CaO	9·05	0·161
Na_2O	2.40	0·039
K_2O	1·03	0·011
H_2O(+110°C.)	1·39	—
H_2O(−110°C)	0.87	—
CO_2	0·32	0·0073
TiO_2	2·63	0·0328
ZrO_2	none	—
P_2O_5	0.32	0·0022
Cl	trace	—
S	0·02	0·0006
Cr_2O_3	0·01	0·0001
V_2O_3	0·05	0·0003
NiO	none	—
MnO	0·10	0·0014
SrO	trace	—
BaO	0·02	0·0001
Li_2O	trace	—
	100·38	
Less O for S	0·01	
	100·37	

Specific gravity = 2·99.

Norm.			
Quartz			9·00
Orthoclase			6·06
Albite			20·29
Anorthite			24·39
Diopside	$CaSiO_3$	6·87	13·19
	$MgSiO_3$	4·74	
	$FeSiO_3$	1·58	
Hypersthene	$MgSiO_2$	8·80	11·74
	$FeSiO_3$	2·94	
Magnetite			6·90
Ilmenite			4·98
Pyrite			0·04
Apatite			0·74
Calcite			0·73
			98·06
Water			2·26
			100·32

Calculated Mineral Composition.

Quartz	9·74
Alkali-felspars, $Ab_{60}Or_{40}$	3·88
Plagioclase, $An_{48}Ab_{42}Or_{10}$	43·44
Pyroxenes	27·61
Ores (as above)	11·92
Apatite	0·74
Calcite	0·73
	98·06

9. THE HETT DIKE-SYSTEM AND THE WACKERFIELD DIKE.

The system of dikes of which the Hett is the longest and only well-known member begins near the Pennine escarpment in Westmorland with two thin and poorly exposed dikes on Long Fell. Nearly in line with these and separated from them by Warcop Fell is the little Connypot dike. The next exposure of a dike is in Yorkshire on the northern slopes of Lunedale, north of Sleight Edge, about four miles from Middleton-in-Teesdale. This is probably a continuation of the dike which is magnificently exposed in the spectacular Greengates quarry, a mile and a half nearer Middleton. The Greengates dike is 40 to 50 feet thick, but appears thicker because it dips to the NNW. at about 60°. In a previous paper the dike has been referred to as the Hett dike (**15**, p. 449), and this may be justified by the fact that it lies nearly in a direct line with the Hett dike. Between the Greengates dike and the Lunedale road a parallel dike occurs, and south of the road there is yet another trending from Thringarth to Bowbank. These two, and also the dike above Sleight Fell, send off sills to the south, and it is therefore not a matter for surprise to find a ten-foot sheet of what may be regarded as the Whin Sill well exposed on both sides of the Lune at and above the first bend above the railway viaduct. Injection to the south of the dikes was, however, on a relatively minute scale, for at Middleton quarries, half a mile to the north-west, the Whin Sill proper is at least 140 feet thick.

The Hett dike courses across Durham from a point a mile beyond the Tees towards the Permian escarpment. The general impression that it continues beneath the Permian is not supported by the evidence, for the dike is not encountered in the colliery workings east of those of Bowburn, south-east of Durham. Moreover, as it is traced through the collieries in depth, and along the lines of disused trench-like quarries at the surface, it is found to be not a continuous structure but a series of at least five members, each one beginning a little to the north of its neighbour to the west, but without overlapping. In some cases it is proved that this is not a result of faulting. The thickness varies from 7 feet at Sunny Brow to twice as much at Tudhoe, after which it thins again eastwards to 9 feet where it is last encountered.

North of the Hett dike, the Ludworth dike is first met with in the Bowburn workings on the Busty level, where it is 33 feet thick. In Sherburn Hill workings, the dike is in two portions, 10 feet apart, 18 and 27 feet thick. Thus thickening as it passes under the Permian, it probably continues to the coast and beyond, for a dike in line with the Ludworth occurs in the Coal Measures near the boundary between Easington and Horden collieries. On account of its position and the presence of a thick selvage of cinder coal flanking it on each side, it has not been worth while for either Company to penetrate the dike.

Still farther north in the Bowburn and Shincliffe workings are the little Shincliffe dikes, only a few feet thick, but thickening westwards where they are found in the Tudhoe workings. The Butterby dike is exposed on the west bank of the Wear, and while it can be traced in the neighbouring collieries it is not in line with the Shincliffe dikes to the east or with the Brandon dike to the west. The latter is the dike mentioned by Bell[1] and referred to by Teall as being two miles north of the Hett dike (**3**, p. 230), where the latter crosses the Wear near Page Bank. It has been traced by the presence of cinder coal in the Wooley and Oakenshaw collieries, and at South Brandon, where it has been cut through in two drifts, it was found to be 6 feet thick in one place, and divided into two sections, each 3 feet thick, in another. Farther east it thickens to 9 feet, but it appears to die out near the Darlington road, where the Butterby dike, 6 or 7 feet thick, takes up the running. The Brancepeth sill encountered in boring operations, and described by Bell and Teall, is apparently a southerly offshoot from the Brandon dike. It reaches a thickness of 20 feet and lies 52 feet above the Busty seam.

The only other intrusions of the Whin Sill type at present known in Durham are the Wackerfield dike five miles south of the Hett, and an intrusion encountered in Castletown colliery on the north side of the Wear west of Sunderland and ten miles north of the Ludworth dike. The Castletown intrusions are irregular sill-like offshoots in the Hutton seam. The dike from which they probably come has not been encountered with certainty, but that there is a dike is rendered certain by two considerations. The Maudlin seam vertically above the Hutton is coked, and coke and cinder coal are found in the Washington Glebe, North Biddick, and Harraton collieries along a line trending WSW., parallel to the general direction of the Wear in this neighbourhood, and to the ninety-fathom fault.

Tectonics.—Even if we leave out of consideration these outlying dikes, it is clear that the Hett group of dikes does not form an echelon system comparable with those already discussed. Local echelons can be detected, but such differential stresses as may be responsible for these were probably local effects superimposed upon a more dominant process of fissure formation. A general uplift of the affected region by a deep-seated introduction of magma would, as shown by Hopkins nearly a century ago,[2] produce simultaneously a system of parallel fissures which would begin in depth and tend to die out upwards. If, in addition, we postulate that the rate of introduction of the magma or the velocity of currents within it was not quite uniform laterally, then the fissures would be expected to develop in either positive or negative[3] echelons according to the direction of lateral decrease of velocity.

---

[1] I. L. Bell, Proc. Roy. Soc. London, 1875, vol. 23, p. 543.

[2] W. Hopkins, Trans. Cambridge Phil. Soc., 1838, vol. 6, p. 34, p. 41 et seq.

[3] The Holy Island echelon is negative (due to a left-handed shear), whereas the High Green echelon is positive (due to a right-handed shear). See S. Fujiwhara, Gerlands Beiträge z. Geophysik, 1927, vol. 16, p. 2.

This conception seems competent to match the requirements of the Hett system, and if we further postulate an easterly magmatic drag on the overlying crust which was effectually more powerful to the north of the Northumbrian block (i.e. north of the Stublick faults) then the St. Oswald's Chapel echelon finds a physical interpretation. A still further increase in the easterly drag north of the Swindon disturbance and its westward virgations (not shown on fig. 1) would in turn explain the High Green echelon. A rapid decrease, or a fall to a uniform flowage, beyond the Cheviots would then be necessary to produce the Holy Island echelon.

This hypothesis implies that the Northumbrian fault block was already a distinct tectonic feature when the dikes were injected, and that it presented a greater and more uniform resistance to the drag to the east than the country to the north as far as the Cheviots. Garwood (**9**, p. 690) and more recently Versey (**26**, p. 11) have both suggested that the Pennine faults were preceded by a sharp monoclinal fold. The steep limb would then present a barrier to the intrusion of the Whin Sill just as happened in the case of the Holburn anticline in the north. Thus we have at least circumstantial evidence supporting the view already put forward that the main folding was earlier than the advent of the Whin Sill. The superior 'rigidity' of the Northumbrian fault block compared with the more easily folded country to the north and south has been emphasized by Prof. J. E. Marr[1] and Prof. O. T. Jones[2] in recent presidential addresses. Thus the conditions are distinctly favourable to the application of the hypothesis here developed.

Petrology.—From Long Fell to Ludworth the dikes all present essentially the same characters as the Wackerfield dike which has previously been described in considerable detail (**15**, p. 447). Except in the thick Greengates dike and the dike to the south there is generally a noteworthy amount of brown mesostasis packed with curved and acicular microlites, and strings of incipient black ores in a background stained with still smaller globulites, but clearing here and there to pale felsitic material. Hypersthene is generally present, and in the Greengates dike it is enclosed in plagioclase. In the dike south of Greengates, however, small felspars are enclosed in altered hypersthene. The phenocrysts of older plagioclase from the Long Fell, Hett, Butterby, and Ludworth dikes have already

---

[1] J. E. Marr, The rigidity of north-west Yorkshire. The Naturalist, 1921, p. 63.

[2] O. T. Jones, The foundations of the Pennines. Journ. Manchester Geol. Assoc., 1927, vol. 1 (for 1925–6), pp. 13-14.

been described on page 502. Teall did not record these from the Hett dike, but the example figured on plate X is from his own Tudhoe specimen (589). The Castletown intrusions are greatly altered by gases from the cindered coal. These do not appear to have become effective until after the magmatic material had crystallized almost normally, for the most altered rocks still retain ghostly reliquiae of the usual textures. The fresh rock (567) contains clear, faintly pleochroic hypersthene, and the same type of brownish mesostasis as the St. Oswald's Chapel dike and the dikes of the Hett group. Micrometric analyses give the following percentages by volume:

Micrometric Measurements of Dikes of the Hett Group.

Dikes.	Pyroxene (P).	Plagioclase (F).	F/(P + F).
596. Long Fell (southern)	34·7	48·0	58 %
614. Greengates[1] ...	30·8	52·3	63
589. Hett, Tudhoe	30·3	49·7	62
617. Butterby	31·1	48·5	61
631. Ludworth	31·8	49·8	61
— Wackerfield[2]	32·2	54·1	63

Chemical Composition.—An analysis of Teall's Tudhoe specimen (589) of the Hett dike is given below. The high carbon dioxide corresponds with Teall's statement that 'Here and there small spherical amygdaloids, for the most part filled with calcite, may be recognised . . . On applying acid, a slight effervescence may frequently be observed' (3, p. 229). Otherwise the analysis is of the usual Whin Sill type. The analysis made for Bell and quoted by Teall gives figures for alumina and potash that are much too high, while only 0·56 per cent. of soda is recorded.

Chemical Composition of the Hett Dike (589).

	Per-centages.	Molecular Proportions.	Norm.			
SiO_2 ...	50·31	0·838	Quartz ...			9·77
Al_2O_3 ...	13·50	0·132	Orthoclase			5·56
Fe_2O_3 ...	3·86	0·024	Albite ...			19·92
FeO ...	8·29	0·115	Anorthite			23·45
MgO ...	4·98	0·123	Diopside	$CaSiO_3$	3·62	7·09
CaO ...	9·63	0·172		$MgSiO_3$	2·06	
Na_2O ...	2·39	0·038		$FeSiO_3$	1·41	
K_2O ...	0·91	0·010	Hypersthene	$MgSiO_3$	10·29	17·39
H_2O (+110° C.)	0·99	—		$FeSiO_3$	7·10	

---

[1] Quoted from 15, p. 449, where it is referred to as the Hett dike, Lunedale.

[2] Average of three determinations (15, p. 449).

	Percentages.	Molecular Proportions.
H_2O (−110° C.)	0·45	—
CO_2	2·24	0·051
TiO_2	2·16	0·027
ZrO_2	none	—
P_2O_5	0·27	0·002
Cl	trace	—
S	0·11	0·003
Cr_2O_3	none	—
V_2O_3	0·05	0·0003
NiO	none	—
MnO	0·12	0·002
SrO	0·02	0·0002
BaO	0·04	0·0003
Li_2O	trace	—
	100·32	
Less O for S	0·04	
	100·28	

Specific gravity = 2·96.

Norm.	
Magnetite	5·56
Ilmenite	4·10
Pyrite	0·18
Apatite	0·67
Calcite	5·10
	98·79
Water	1·44
	100·23

Calculated Mineral Composition.

Quartz	10·48
Alkali-felspars, $Ab_{60}Or_{40}$	3·05
Plagioclase, $An_{47}Ab_{43}Or_{10}$	42·53
Pyroxenes	27·10
Ores	9·84
Apatite	0·67
Calcite	5·10
	98·77

The analysis of the Wackerfield dike made in **1921** (**15**, p. **451**) is repeated here for completeness. It is clearly of exactly the same type as the others of the series.

Chemical Composition of the Wackerfield Dike (606).

	Percentages.	Molecular Proportions.
SiO_2	50·30	0·837
Al_2O_3	14·11	0·138
Fe_2O_3	3·16	0·020
FeO	9·90	0·138
MgO	5·56	0·138
CaO	8·54	0·152
Na_2O	2·34	0·038
K_2O	0·74	0·008
H_2O (+105° C.)	1·94	—
H_2O (−105° C.)	1·01	—
CO_2	0·16	0·004
TiO_2	2·22	0·028
ZrO_2	trace	—
P_2O_5	0·30	0·002
Cl	trace	—
S	none	—
MnO	0·12	0·002
SrO	none	—
BaO	0·03	0·0001
	100·43	

Specific gravity = 2·98.

Norm.			
Quartz			5·82
Orthoclase			4·45
Albite			19·92
Anorthite			25·59
Diopside	$CaSiO_3$	5·81	11·46
	$MgSiO_3$	3·01	
	$FeSiO_3$	2·64	
Hypersthene	$MgSiO_3$	10·84	20·34
	$FeSiO_3$	9·50	
Magnetite			4·63
Ilmenite			4·25
Apatite			0·67
Calcite			0·40
			97·53
Water			2·95
			100·48

Calculated Mineral Composition.

Quartz	6·78
Alkali-felspars	none
Plagioclase, $An_{47}Ab_{44}Or_9$	45·50
Pyroxenes	32·25
Ores	8·88
Apatite	0·67
Calcite	0·40
	97·48

10. GEOLOGICAL AGE OF THE INTRUSIONS.

The evidence already presented indicates that the Whin Sill and the dikes described in this paper are composed throughout of substantially identical material. The chemical evidence is summarized in the following table in which, for easy reference, all the new analyses are placed side by side and averaged. It is clearly impossible to pick out a single detail in which there is any essential difference between the rocks analysed, and that the analysis of the Whin Sill is representative of the whole is shown conclusively by the table on page 513.

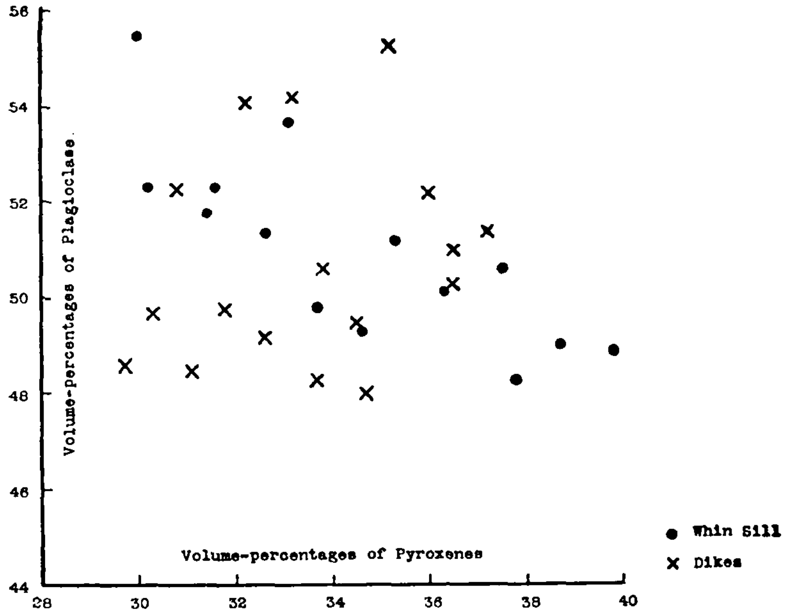


FIG. 3. Proportions of Pyroxenes and Plagioclase in the Whin Sill and Dikes.

The proportions of pyroxenes and plagioclase are also closely alike throughout the series. This fact is strikingly displayed by fig. 3, in which the range of variation in the Whin Sill (marked by dots) is seen at a glance to be almost the same as that in the dikes (marked by crosses). The range of the plagioclase for an average amount of pyroxene is a little greater in the case of the dikes, because in some of the latter the degree of crystallization is not so complete as in most of the measured Whin Sill specimens. Judging from the analyses, the plagioclase must be always overestimated, as is natural, but as the results are affected by the same personal equation throughout they are comparable among themselves. The Bingfield rock, it should be noted, falls outside the diagram, like most of the north of England tholeiites.

Analyses of the Whin Sill and Related Dikes and of a Pebble of Similar Type.

(By H. F. Harwood.)

	A.	B.	C.	D.	E.	F.	Av. (A–F).	Pebble, G.
SiO_2 ...	51·04	50·77	49·59	51·13	50·31	50·30	50·52	51·43
Al_2O_3	13·69	13·64	13·66	13·96	13·50	14·11	18·76	13·79
Fe_2O_3	2·97	3·17	5·29	4·76	3·86	3·16	3·87	6·25
FeO ...	9·12	8·87	7·90	6·88	8·29	9·90	8·50	6·71
MgO ...	5·75	5·66	5·09	5·44	4·98	5·56	5·42	5·57
CaO ...	9·46	8·44	9·34	9·05	9·63	8·51	9·09	8·89
Na_2O ...	2·27	2·83	2·27	2·40	2·39	2·34	2·42	2·29
K_2O ...	1·01	1·19	0·91	1·03	0·91	0·74	0·96	0·82
H_2O+	1·48	1·61	1·51	1·39	0·99	1·94	1·51	2·05
H_2O-	0·37	0·75	1·13	0·87	0·45	1·01	0·76	0·45
CO_2 ...	0·29	0·02	0·52	0·32	2·24	0·16	0·58	—
TiO_2 ...	2·22	2·49	2·59	2·63	2·16	2·22	2·39	2·38
ZrO_2 ...	none	none	none	none	none	trace	—	—
P_2O_5 ...	0·30	0·28	0·10	0·32	0·27	0·30	0·26	—*
Cl ...	trace	trace	trace	trace	trace	trace	—	—
S ...	0·12	0·05	0·05	0·02	0·11	none	0·06	—
Cr_2O_3 ...	none	trace	none	0·01	none	—	—	—
V_2O_3 ...	0·06	0·05	0·05	0·05	0·05	—	0·05	—
NiO ...	none	none	none	none	none	none	—	none
MnO ...	0·22	0·15	0·25	0·10	0·12	0·12	0·16	—
SrO ...	trace	none	trace	trace	0·02	none	—	0·01
BaO ...	0·03	0·03	0·01	0·02	0·04	0·03	0·03	—
Li_2O ...	trace	trace	trace	trace	trace	—	—	—
	100·40	100·00	100·26	100·38	100·32	100·43	100·34	100·64
Less O	0·04	0·02	0·02	0·01	0·04	—	0·03	—
	100·36	99·98	100·24	100·37	100·28	100·43	100·31	100·64

* P_2O_5 is included in Al_2O_3 in this analysis.

A. Whin Sill, Scordale Beck, Westmorland.
B. Holy Island Dike, The Castle, Holy Island, Northumberland.
C. Elsdon Dike, Grasslees Burn, Northumberland.
D. St. Oswald's Chapel Dike, St. Oswald's Chapel, Northumberland.
E. Hett Dike, Tudhoe, Durham.
F. Wackerfield Dike, Durham.
Av. Average of the six analyses A–F.
G. Pebble of quartz-dolerite from the Upper Brockram, George Gill, Brackenber Moor, near Appleby, Westmorland.

If we deduce from the evidence that the sills and dikes came from the same magma, then we may proceed to admit that the injection of both types of intrusion was as exactly simultaneous as can ever be asserted of correlated geological events. The presence in both of more or less corroded phenocrysts and aggregates of highly anorthitic felspar, showing throughout exactly the same reaction phenomena, and the presence in both of the same types of pyroxenes, provide cumulative evidence of contemporaneous consolidation from a magma of exceptional uniformity. It has not yet been proved that the visible dikes are the feeders of the Whin Sill, though it is highly probable that they functioned in that way. The Kyloe-Farne Islands crescent seems to be intimately related with the Holy Island echelon, and the non-appearance of the sill south of Alnwick beyond the line of the Flamborough and Hampeth dikes may be equally significant. But in the Pennines it seems probable that in addition to the visible dikes, to the north and south, there are also hidden feeders not represented at the surface.

Following the sound opinion of William Gunn (**23**, p. 119) it has been generally recognized that the time of intrusion is to be referred to the period of denudation represented by the unconformity between the Upper Carboniferous and Permian strata of the north of England. The Durham dikes cut the Middle Coal Measures, so that they are definitely post-Westphalian. The upper limit, however, has hitherto not been well established. The fact that the Ludworth dike is not known to cut the Permian is not conclusive, for it may die out vertically, as the Hett dike does laterally, before the Permian rocks are reached. Better evidence, though less close, is provided by the relations of the ore-deposits to the Whin Sill on the one hand and the Cleveland dike on the other.

In the extreme north of the area veins have been found cutting the Whin Sill in the Farnes and on the adjoining mainland (**23**, p. 160). In central Northumberland the vein of the Quarryhouse lead mine cuts the Whin Sill (**18**, p. 17). In the South Tyne valley the Settlingstones mines were mainly productive within the Whin Sill (**18**, p. 27). The Tynebottom and Rotherhope Fell mines followed veins through it, and the Great Sulphur Vein is a mineralized shatter-belt which breaks through the Whin. In Weardale the Whin Sill carries pockety ore bodies in the Burtree Pasture mine, but the Slitt vein closes in and is unproductive within the sill (**19**, pp. 5–6). In Upper Teesdale the Greenearth mine was highly productive in the Whin Sill (**19**, pp. 23–24). Across the watershed the veins worked in the Dufton Fell and Scordale mines visibly cut through the sill, and in the latter mine fragments of the rock have been found in a vein of baryte. Many of the dikes are also cut by mineral veins, among them being the High Green, Hett, Brandon, and Shincliffe dikes. It is therefore beyond all doubt that the period of mineralization, correlated by Finlayson with the generalized Hercynian metallogenic period (**10**), is later than the Whin Sill and its dikes.

Teall pointed out that the Cleveland dike has in all probability cut through the Whin Sill near Tyne Head (**3**, p. 212), and although no actual contact can be seen in the field the deduction cannot be doubted. However, in this neighbourhood the dike cuts through the north-easterly Douks Burn vein without dislocating it. Dr. Stanley Smith points out the great interest of this observation, which was made by Prof. H. Louis. 'It is', he writes, 'practically the only definite evidence we have in the North of England from which the relative age of the mineralisation can be deduced' (**18**, pp. 95–96).

Fortunately, since then, the evidence of detrital minerals has established the age of mineralization more closely. Baryte, both authigenic and allogenic, occurs in the Yellow Sands underlying the Magnesian Limestone of Yorkshire. H. P. Lewis[1] considered it improbable that the lead-zinc veins could have supplied the material on account of the apparent absence of fluorite. In a later investigation by Versey[2] triangular fragments of fluorite were found sparingly all along the outcrops of the Yellow Sands of Yorkshire.[3] Authigenic baryte occurs in the Coal Measures and Millstone Grit, but fluorite has not been detected in these formations. The appearance of detrital fluorite in the Yellow Sands therefore implies that the main deposition of the ores had already been accomplished. Ore-deposition locally continued into the Permian, but only as an insignificant after-effect. The general mineralization followed the intrusion of the Whin Sill and preceded the formation of the Yellow Sands. Gunn's estimate of the age of the Whin Sill is thus confirmed.

Direct proof of the validity of this conclusion was established by the writer's discovery in 1925 of a pebble of quartz-dolerite in the Upper Brockram of Brackenber Moor, near Appleby, and its identification with the Whin Sill type. The pebble came from an exposure immediately north-west of a little cave excavated in the south bank of George Gill. (Westmorland, Six-inch Sheet XV N.E.; Lat. 54° 33′, Long. 2° 26′ 15″.) The pebble was stained red like the matrix of the conglomerate and was

---

[1] H. P. Lewis, Geol. Mag., 1923, vol. 60, p. 307.

[2] H. C. Versey, Proc. Yorks. Geol. Soc., 1925, vol. 20, p. 207.

[3] The Yellow Sands of Durham and the Penrith Sandstone of the Eden Valley have as yet yielded (of the ore-minerals) only a little baryte, and no fluorite.

oval in shape, the dimensions being 25 × 21 × 11 millimetres. The larger of two pieces into which the pebble was broken provided the material for a chemical analysis. The remaining fragment (557), weighing 3·5 grams, after a thin section had been cut from it, is preserved for reference.

The thin section shows dispersed iron-staining and a thin band of more concentrated alteration from 1 to 2 mm. within the periphery. The grain size is unusually low, averaging about 0·12 mm. See plate X, fig. 6. The pyroxenes are the usual altered hypersthene, the stumpy prisms of hypersthene-augite, and the more abundant plates and granular aggregates of later augite characteristic of the Whin Sill. Iron-staining is seen to result mainly from the production of limonite within the pyroxenes. Some of the clear plates of later augite which have escaped alteration show a faint purple tint which is also to be seen in the Whin Sill of Scordale. The felspars are fairly fresh. The ores are well individualized and have suffered only a little superficial hydration. For the fine-grain of the rock the percentage of mesostasis is surprisingly low, and very few globulites are present in comparison with their abundance in sections of the Long Fell dikes in which the mesostasis also is particularly conspicuous. The pebble can therefore not have been derived from these dikes.

The results of a chemical analysis of a washed fragment of the pebble carried out as fully as the limited amount of material made possible are presented in the table on page 530, where they can be easily compared with those of the analyses of the Whin Sill type. It will be seen at a glance that, allowing for the effects of weathering, the pebble is also of the Whin Sill type. The only significant differences are the higher ferric oxide (the total iron being of the right order) and the higher water, corresponding to the production of limonite within the pebble.

In every determinable respect the pebble corresponds with a fine-grained variety of the Whin Sill. As to its provenance, the Christy Bank exposure against the fault that runs along Swindale Beck behind Roman Fell provides the most promising clue.[1] The fault has a downthrow to the north and is clearly later than the intrusion of the Whin Sill. The feather edge of the sill may therefore be reasonably supposed to have originally penetrated the rocks to the south-west of the present fault, but to have faded out before reaching the steep limb of the ancestral Pennine monocline. This would imply the former presence of the attenuated Whin Sill in Carboniferous strata lying originally vertically

---

[1] See map by E. J. Garwood, Quart. Journ. Geol. Soc. London, 1912, vol. 68, p. 536, and reproduced by Gilligan (22, p. 18); and map by J. S. Turner (24).

above the site of Roman Fell, strata that have since been entirely removed by denudation. The interpretation suggested is in accordance with the conclusions of Kendall[1] and Versey (**26**, pp. 14–16) as to the origin of the Upper Brockram. However, in view of Turner's recent opinion that the Brockram materials came from the Lake District or Howgill Fells (**24**), further work on the pebbles and distribution of the Upper Brockram is in progress.

The Whin Sill rock has not previously been recorded from the Upper Brockram, and it was evidently by unusual good fortune that the pebble here described was found. Several days have since been spent in searching for others, but without success. The pebble is not, however, absolutely unique, for during the discussion of this paper Dr. Leonard Hawkes made the interesting announcement that he had found a pebble of the same type in the Upper Brockram some years ago, and that the late Dr. David Woolacott, who was present at the time, also identified the pebble with the rock of the Whin Sill.

We have now established the age of the Whin Sill intrusion as lying between the Westphalian and part of the Penrith Sandstone (Saxonian). Consideration of the tectonics of the region narrows the limits still further. Reasons for regarding the main folding and the first associated faults in the Holburn, Swindon, Stublick, Burtree Ford, and Pennine disturbances as older than the intrusions have already been given.[2] Weyman has also shown the probability that the Whin Sill is later than the folding in the neighbourhood of Gunnerton (**11**) and Kirkwhelpington (**13**). The latest formations known to be affected by this phase of folding are Westphalian. After the intrusion, and during and after the mineralization of the district, faulting took place on an important scale, and wherever there is the possibility of evidence the movements can be shown to be at least in part of pre-New Red age.[3] The synclinal folding of the Coal Measures beneath the Permian of the Durham coast (parallel to the Pennine and Holburn axes) and the greater part of the associated faulting are definitely pre-Yellow Sands. We therefore have the following sequence of events:

5. Saxonian Upper Brockram and Yellow Sands;
    4. Faulting movements accompanied by the main deposition of ore-deposits.

---

[1] P. F. Kendall, Geol. Mag., dec. 4, vol. 9, 1902, pp. 510–513.

[2] See also H. C. Versey, 26.

[3] See Mem. Geol. Survey, The Geology of the Carlisle, Longtown, and Silloth district, 1926, pp. 41–42.

3. Intrusion of Whin Sill and dikes.
2. Folding movements accompanied by faulting.
1. Westphalian Coal Measures.

This sequence can be correlated in a general way with part of Stille's summary of the Variscan phases of orogenesis :[1]

Permian.	*Pfälzische Faltung.*		
	Zechstein	Thuringian	Magnesian Limestone
	Upper Rotliegend	Saxonian	*Penrith Sandstone*
	Saalische Faltung.		
	Lower Rotliegend	Autunian	Unrepresented in the north of England by sediments
Upper Carboniferous	Ottweiler	Stephanian	
	Asturische Faltung.		
	Saarbrücker	Westphalian	Middle Coal Measures
	Waldenburger	Namurian	Lower Coal Measures
	Sudetische Faltung.		

Without entering into discussion of the vexed questions of the exact contemporaneity of orogenic movements in neighbouring areas, or of the correlation of beds generally regarded as Permian, it seems not unreasonable to propose provisionally

(*a*) that the intrusion of the Whin Sill and the related dikes followed closely on the Asturian movements ; and

(*b*) that the mineralization was associated with the Saalian movements.

The injection of the Whin Sill and the related dikes may thus be regarded as the closing act of the Upper Carboniferous in the north of England. It is not intended to speculate on the origin of the ore-deposits that followed, but it should perhaps be said that there is no evidence that they can have been derived from the magma which gave rise to the Whin Sill type of rock. In Cornwall and Devon there is a sequence of events very like that of the north of England, with the important addition of a series of granitic intrusions preceding the formation of the ore-deposits. The quartz-dolerites of the north of England seem to have no more to do with the mineralization than their analogues in the south-west.

11. THE MAGMA-TYPE AND ITS DISTRIBUTION.

The Whin Sill magma-type, represented by the analyses in the table on page 530, is one that, with only minor variations of some of the constituents, is of world-wide distribution, the rocks produced being

---

[1] H. Stille, Grundfragen der vergleichenden Tektonik. 1924, p. 83. For a valuable review see C. Schuchert, Amer. Journ. Sci., 1926, ser. 5, vol. 12, p. 277.

dikes and sheets of quartz-dolerite, and, in the great plateau-basalt regions, lava-flows of corresponding composition and mineralogical character. Among British examples the great suite of E.-W. quartz-dolerite dikes and sheets of the Midland Valley of Scotland are already familiar from the work of two generations of geologists.[1] Their age is the same as that of the Whin Sill set of intrusions. Particular examples have been described in detail by Dr. J. D. Falconer and Dr. G. W. Tyrrell, and analyses from their papers are reproduced below. South of the Whin Sill the only analysed representative of the type is from the St. David's area, investigated by Dr. J. V. Elsden. That the type is by no means restricted to the late Carboniferous is made clear by its occurrence among the Tertiary plateau basalts of Scotland and Ireland; and among the older rocks the Scourie dike, made classic by Teall, is clearly a metamorphosed representative. Analyses of these rocks are also included in the table below.

In comparing the rocks of plateau-basalt regions indiscriminate averaging is apt to be misleading. There are two main types of plateau-basalt (with continuous variation between them), according as they (*a*) contain olivine phenocrysts or (*b*) correspond with the quartz-dolerites and are free from olivine, except such early products of crystallization as were preserved by rapid cooling from resorption. Each of these in turn may be porphyritic in respect of plagioclase or pyroxene or both, but it is noteworthy that the porphyritic types of (*b*) are more especially characteristic of localized central eruptions. The general absence of phenocrysts in rocks from the quartz-doleritic or Whin Sill type of magma is one of their most characteristic features. In the Whin Sill the relics of earlier phenocrysts show that the magma is not a parent magma, but a close approach towards a natural end-product. The mineral composition of the pegmatitic veins here and elsewhere shows that after the crystallization of hypersthene and hypersthene-augite the residual magma remains nearly stationary in composition as regards the balance of plagioclase, pyroxenes, and ores. It is still apparently possible for the ternary eutectic of Q–Or–Ab to be separated in small quantities, producing rare leucocratic veins, but apart from this there is no further significant differentiation.

---

[1] Mems. Geol. Survey Scotland: Cowal, 1897, p. 147; The neighbourhood of Edinburgh, 1910, pp. 282 and 301; and The Glasgow district, 1925, pp. 153 and 186.

Analyses of British Rocks of the Whin Sill Type.

	A.	B.	C.	D.	E.	F.
SiO_2	50·54	49·80	48·02	50·52	50·55	49·78
Al_2O_3	12·86	17·77	13·03	13·76	15·00	13·13
Fe_2O_3	4·13	2·29	2·11	3·87	2·54	4·35
FeO	8·75	8·75	9·99	8·50	7·90	11·71
MgO	4·63	5·67	4·21	5·42	6·25	5·40
CaO	8·74	8·85	9·77	9·09	7·85	8·92
Na_2O	2·89	1·48	2·17	2·42	3·53	2·39
K_2O	1·43	0·48	0·49	0·96	1·10	1·05
H_2O + ...	2·25	2·62	4·27*	1·51	3·14	1·14
H_2O − ...	0·17	1·04	1·05	0·76	0·55	
CO_2	—	—	n.s.d.	0·58	—	0·10
TiO_2	2·80	1·56	3·36	2·39	1·58	2·22
P_2O_5	0·34	trace	0·40	0·26	—	—
MnO	0·32	trace	trace	0·16	—	—
Incl.	0·39	—	—	0·11	—	—
...	100·24	100·31	100·16	100·31	99·99	100·19

* Includes CO_2.

A. Basalt, Tertiary, Mull. E. G. Radley, analyst. (Mull Memoir, 1924, analysis IV, p. 17.)
B. Quartz-dolerite (Granophyric diabase), Late Carboniferous, Auchinstarry, Kilsyth, Dumbarton, Midland Valley of Scotland. D. P. Macdonald, analyst. (G. W. Tyrrell, Geol. Mag., 1909, dec. 5, vol. 6, p. 361.)
C. Quartz-dolerite, *dark-coloured modification*, Late Carboniferous, Kettlestown quarry, Bathgate Hills, Midland Valley of Scotland. J. D. Falconer, analyst. Trans. Roy. Soc. Edinburgh, 1906, vol. 45, p. 148.
D. Quartz-dolerite of the Whin Sill and related dikes, Late Carboniferous. Average of six analyses by H. F. Harwood.
E. Quartz-gabbro (intermediate type), probably Late Carboniferous, east flank of Carn Llidi, St. David's, Pembrokeshire. J. V. Elsden, analyst. Quart. Journ. Geol. Soc. London, 1908, vol. 44, p. 281.
F. Hornblende-schist, metamorphosed facies of dolerite dike, age Pre-Devonian. Scourie, Sutherland. J. J. H. Teall, analyst (7, p. 200).

The 'parent' basaltic magma may be regarded as being in general a potentially olivine-bearing type ; by partial crystallization and the separation of phenocrysts from the magma, the latter becomes oversaturated and passes steadily into the Whin Sill type. In a four-dimensional cooling diagram the liquid then appears to have closely approached or reached the groove of minimum temperature as between the three systems plagioclase, pyroxenes, and ores. While further consolidation takes place the liquid moves down the groove towards the lower temperature at which micropegmatite crystallizes. Since over this stage there is no important change of composition, the groove must dip very steeply towards the four-dimensional eutectic point at which micropegmatite appears, and by the time this point is reached most of the other constituents have crystallized out. It is in this sense that the oversaturated basaltic magma of the Whin Sill type is to be regarded as very nearly an end-product of differentiation. The additional effects of uprising fluxes in the cauldrons of central intrusions and volcanoes may, of course, alter the distribution and balance of the constituents very considerably, so in all probability producing the association of trachybasalt and trachyte that is now known to be characteristic of many central eruptions. In the plateau-basalts, however, the oversaturated type tends to become constant in composition, whereas the undersaturated olivinic types may vary over a far wider range of composition.

For the reasons stated above it is not desirable to compare the *average* analyses of plateau-basalts compiled by Washington[1] with the Whin Sill type. Many of the rocks considered by him are olivine-bearing, and magnesia therefore tends to be relatively high. The Deccan average is nevertheless remarkably like the Whin Sill composition, but in the composite analysis given below only six analyses have been averaged. Of the others, nos. 1, 5, and 6 are of late Tertiary flows; no. 8 is undersaturated; and no. 21 is a Rajmahal Gondwana lava of Upper Triassic or Lower Jurassic age, and therefore does not belong to the Deccan traps. Among older Indian rocks of the Whin Sill type Holland's 'augite-diorite' dikes, believed to be associated with the Cuddapah basalts, have already been referred to.[2]

In the Thulean or Brito-Arctic province the plateau-basalts are very frequently olivine-bearing. The example already cited from Mull is a typical member of the 'non-porphyritic central magma-type' of the Survey, and corresponds with the Whin Sill in its general characters. The chemically not very dissimilar Staffa type differs in that many of the rocks referred to it contain olivine. In other parts of the province the type is represented by rocks from Iceland and Spitzbergen, analyses of which are quoted for comparison.

The quartz-dolerites of the Triassic Palisadan province east of the Appalachians, and the corresponding flows, are identical with the Whin Sill type. The analysis quoted is that of the normal rock of a sill which has received from Shannon a more thorough investigation than any other of the numerous intrusions of this region. Teall referred with obvious interest to the striking similarity between the Whin Sill and many of

---

[1] H. S. Washington, Bull. Geol. Soc. Amer., 1922, vol. 33, p. 797.

[2] T. H. Holland, Quart. Journ. Geol. Soc. London, 1897, vol. 53, p. 409.

Analyses of Basalts and Quartz-dolerites of the Whin Sill Type.

	A.	B.	C.	D.	E.	F.
SiO_2	50·52	49·68	48·79	50·17	51·56	51·19
Al_2O_3	13·76	12·95	11·96	13·66	13·81	15·80
Fe_2O_3	3·87	3·47	2·51	5·40	0·96	3·08
FeO	8·50	10·10	12·10	6·59	11·32	11·20
MgO	5·42	5·69	5·60	5·31	7·40	5·63
CaO	9·09	10·09	10·15	9·26	10·08	9·58
Na_2O	2·42	2·27	2·40	2·06	2·08	2·09
K_2O	0·96	0·52	0·70	1·00	0·96	0·60
H_2O+	1·51	1·71	0·40	1·28	—	0·30
H_2O-	0·76	0·29	0·65	1·02	—	
CO_2	0·58	—	0·41	0·44	—	none
TiO_2	2·39	2·60	4·17	2·93	1·48	0·40
P_2O_5	0·26	0·33	0·37	0·28	0·16	0·01
MnO	0·16	0·20	0·21	0·15	0·19	trace
Incl.	0·11	0·04	0·15	0·38	—	—
	100·31	99·94	100·57	99·93	100·00	100·88

A. Average Whin Sill type: six analyses by H. F. Harwood (this paper).

B. Average Deccan Basalt, H. S. Washington's analyses 4, 12, 13, 15, 16, 23 in Bull. Geol. Soc. Amer., 1922, vol. 33, p. 774.

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

D. Quartz-dolerite sill, Sassendal, central Spitzbergen. H. F. Harwood, analyst. (Ibid., p. 206.)

E. Quartz-dolerite sill, Goose Creek, Virginia, U.S.A. E. V. Shannon, analyst. Proc. U.S. Nat. Mus., 1924, vol. 66, art. 2, p. 13.

F. Quartz-dolerite dike, Potaro River, British Guiana. J. B. Harrison, analyst. Geology of the goldfields of British Guiana, 1908. [Washington's Tables, 1917, p. 647.]

the New Jersey and Connecticut examples (**4**, p. 657). The type is also represented in North America in dikes and flows of Keewatin, Keweenawan, and Tertiary (Oregonian) age. In South America the Pre-Cambrian basement and the Kaieteur plateau of British Guiana is injected with thick sills and dikes many of which are quartz-dolerites, and these in turn closely resemble the corresponding post-Triassic intrusions of Brazil.[1] The British Guiana intrusions were first made familiar by Harrison, who provided many analyses, one of which is here reproduced. Farther south the Patagonian and Argentine plateau-basalts contain representatives of the type, but the only analysed specimen is olivine-bearing. In South Africa the type is well represented among the Karroo

---

[1] S. Bracewell, Report on the preliminary geological survey of the Potaro-Ireng district of British Guiana. Georgetown, Demerara, *1927*, Combined Court, no. 21.

dolerites, a general study of which has been made by du Toit.[1] He shows that the invasion of magma terminated a long sedimentary period; was accompanied by intense crumpling directed towards the upraised and injected area; and was followed by subsidence of the region from which the pressure came. This movement of the magma apparently in advance of the folded belt, followed by subsidence behind, is curiously like the process that has been deduced in the north of England. Here it was argued from the echelons that the deep-seated magmatic flow was towards the east or north-east; injection occurred to the east of the Holburn and Pennine folds and was followed by relative down-faulting of the country to the west.

Attention is also directed by du Toit to the very similar olivine-free Jurassic dolerites of Tasmania.[2] Those of the Falkland Islands are stated to be olivine-bearing.[3] The thick dolerite sills in the Beacon Sandstone of South Victoria Land, Antarctica, described by Prior,[4] also include examples of the Whin Sill type, though chemically the analysed specimens are richer in silica, lime, and magnesia. A chemically closer parallel with the Whin Sill type is exhibited in Antarctica by the metamorphosed dikes of Cape Denison and Cape Gray in Adélie Land, though mineralogically the rocks vary from amphibolites to pyroxene-gneisses according to the degree of metamorphism they have suffered.[5] In addition to these and the Scourie dike already mentioned, a granulitic amphibolite of dike-like form from Bunker Bay, Western Australia, may also be mentioned as a metamorphosed Whin Sill type which has been analysed.[6]

Many other local examples could be cited,[7] but sufficient has now been said to demonstrate the world-wide continental distribution of the Whin Sill type of magma, and its occurrence throughout the whole range of geological time. It is equally of interest to notice that the type has not

---

[1] A. L. du Toit, Trans. Geol. Soc. South Africa, 1920, vol. 33, pp. 1–42.

[2] See for recent accounts A. N. Lewis, Proc. Roy. Soc. Tasmania, 1927, for 1926, pp. 1–24; and 1928, for 1927, pp. 197–202.

[3] H. A. Baker, Final report on geological investigations in the Falkland Islands (1920–1922), p. 26.

[4] G. T. Prior, National Antarctic Expedition, 1907, vol. 1, p. 137.

[5] F. L. Stillwell, The metamorphic rocks of Adelie Land. Australian Antarctic Expedition, Sci. Rep. A, 1918, vol. 3, pt. i, pp. 41 and 183 respectively.

[6] M. Aurousseau, Proc. Linnean Soc. N.S.W., 1926, vol. 51, p. 625.

[7] See for example the general discussions by G. W. Tyrrell, Geol. Mag., 1909, dec. 5, vol. 6, pp. 362–366; and W. N. Benson, The tectonic conditions accompanying the intrusion of basic and ultrabasic rocks. Mem. Nat. Acad. Sci. U.S.A., 1926, vol. 19, no. 1.

been detected in any of the oceanic islands of the Atlantic, Pacific, or Indian Oceans. The few rocks that approach it chemically are characterized everywhere by notably high alkalis.[1] If the parent magma be basaltic, as it generally appears to be, then differentiation under the marked central conditions of such islands must follow a totally different course, influenced in all probability by the ascent of volatile fluxes through the underlying magmatic cauldrons.

From the geological standpoint perhaps the most significant conclusion of our study is the recognition that under appropriate continental conditions basaltic magma differentiates towards the Whin Sill magma-type, and thereafter remains almost unchanged until the final residuum is squeezed out as rare leucocratic veins. This implies not only the pre-existence of a deep-seated parent magma, but also the deep-seated *cooling* of that magma before its later injection into the crust as the Whin Sill type. Further, evidence has been presented that in the north of England the deep-seated magma moved eastwards at laterally varying rates. From quite different considerations du Toit is led to speak of the forward advance of the magma. Combining these conclusions we reach the conception of a lateral movement of magma beneath the 'sial', cooling as it proceeds. Though there are other possibilities, it is worthy of notice that such a result would be a direct consequence of convection currents in the substratum underlying the 'sial', and since evidence bearing on their possible existence is likely to be gleaned from studies in petrogenesis, the hypothesis is here put forward tentatively, in order that its implications may not be overlooked in the course of other investigations.

Acknowledgements.—Our thanks are due (on behalf of Dr. Harwood) to Professor H.B. Baker for providing facilities for carrying out the analytical work in the laboratories of the Imperial College; and (on behalf of Professor Holmes) to Lady Teall for the privilege of taking charge of, and studying, an important part of the late Sir Jethro Teall's north of England collection; to Dr. W. Hopkins for helpful co-operation in the field and underground; to Mr. A. E. Phaup for his assistance in visiting several collieries; and to Mr. S. Tomkeieff and Mr. G. S. Mockler, of Armstrong College, for permission to record certain of their unpublished micrometric analyses.

---

[1] See in particular, for recent analyses, A. Lacroix, La constitution lithologique des îles volcaniques de la Polynésie australe. Mém. Acad. Sci. Paris, 1927, vol. 59; and R. A. Daly, Proc. Amer. Acad. Arts and Sci., 1927, vol. 62, no. 2.

EXPLANATION OF PLATE X.

Magnification × 20. Ordinary light, except fig. 1, which is between crossed nicols.

FIG. 1. *Quartz-dolerite* (no. 589). Hett dike, Tudhoe, Durham. The field illustrates one of the rare glomeroporphyritic aggregates of bytownite (free from inclusions) as seen between crossed nicols (p. 502). The corroded type with inclusions has been figured in the Geol. Mag., 1921, vol. 58, pl. VIII, fig. 3.

FIG. 2. *Quartz-dolerite* (no. 572). Elsdon dike, Grasslees Burn, Northumberland. The minerals and general appearance here displayed are characteristic of most well-crystallized specimens from the Holy Island and High Green series of dikes (p. 519).

FIG 3. *Quartz-dolerite* (no. 573). St. Oswald's Chapel dike, near Brunton, Northumberland. The black ores are smaller and more numerous than in the rock of fig. 2, and this fact, together with the presence of mesostasis, accounts for the darker aspect of the section (p. 522).

FIG. 4. *Tholeiite of the Brunton type* (no. 369), from the type occurrence in the Bingfield dike, Redhouse Burn, near Bingfield, Northumberland. Pyroxene and plagioclase are segregated into groups, 'partly in contact with one another, and partly separated by mesostasis' [1] (p. 521). The type is also figured by Teall, Q.J.G.S., 1884, vol. 40, pl. XII, fig. 6; and by Harker, Petrology for Students, 1908, fig. 54, and 1919, fig. 62.

FIG. 5. *Quartz-dolerite* (no. 551). The Whin Sill, Scordale Beck, Pennine escarpment south-east of Appleby, Westmorland. This is a typical field of the fine-grained variety of the Whin Sill rock, plagioclase, pyroxenes, ores and interstitial felsic minerals, and mesostasis being present (p. 511).

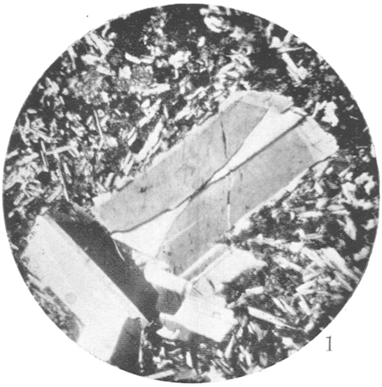
FIG. 6. *Quartz-dolerite* (no. 557). Pebble from the Upper Brockram of George Gill, south of Brackenber Moor, near Appleby, Westmorland. The minerals present are identical with those of fig. 5, but the grain is finer. Pyroxenes are not well reproduced, because of iron-staining. The large black patch, for example, is an altered hypersthene, not titanomagnetite. Seen between crossed nicols the textures of figs. 5 and 6 are found to differ in no essential respect save that of grain size (p. 533).

Note.—Typical fields of the Wackerfield dike, Durham, and of the Little Whin Sill of Upper Weardale, Durham, have been figured in the Geol. Mag., 1921, pl. VIII, facing p. 454. In his British 'Petrography', 1888 (pl. XIII, fig. 2), Teall figured a section of the Whin Sill from Middleton-in-Teesdale which shows in colour the contrast between the rhombic and dominant pyroxenes, and the characteristic alteration of the former.

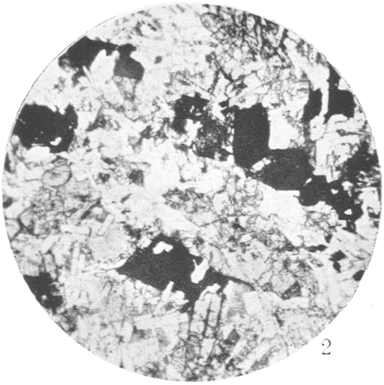
Acknowledgements.—The photomicrographs, here reproduced, were prepared by Mr. G. S. Sweating of the Geology Department of the Imperial College (figs. 3–6) and by Mr. G. O'Neill of the Geology Department of the Durham Colleges (figs. 1 and 2), from thin sections which, together with a large number of others, were made for this investigation by Mr. O'Neill. For the willing and efficient services thus rendered we desire to add a special word of acknowledgement and thanks.

---

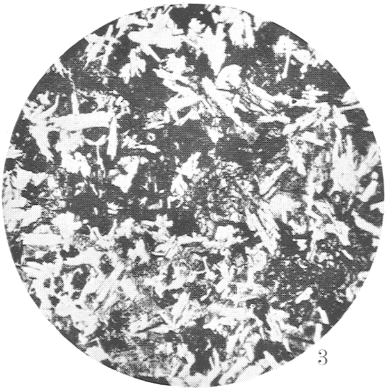
[1] Mull Memoir, 1924, p. 285, quoted from the definition of the type.



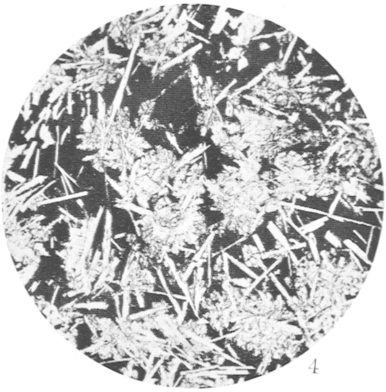
1



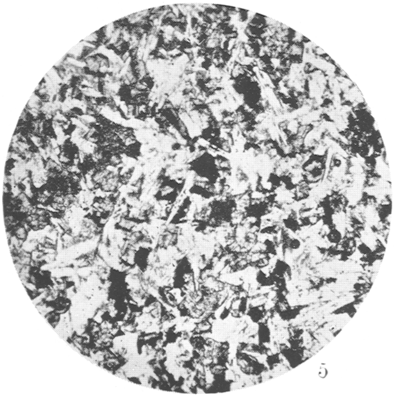
2



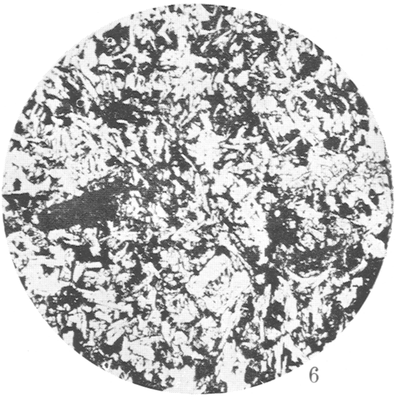
3



4



5



6

A. HOLMES AND H. F. HARWOOD : THE WHIN SILL
AND RELATED DIKES.