

44. *On the CHEMICAL and MICROSCOPICAL CHARACTERS of the WHIN SILL.* By J. J. H. TEALL, M.A., F.G.S. (Read June 25, 1884.)

[PLATE XXIX.]

LITERATURE.

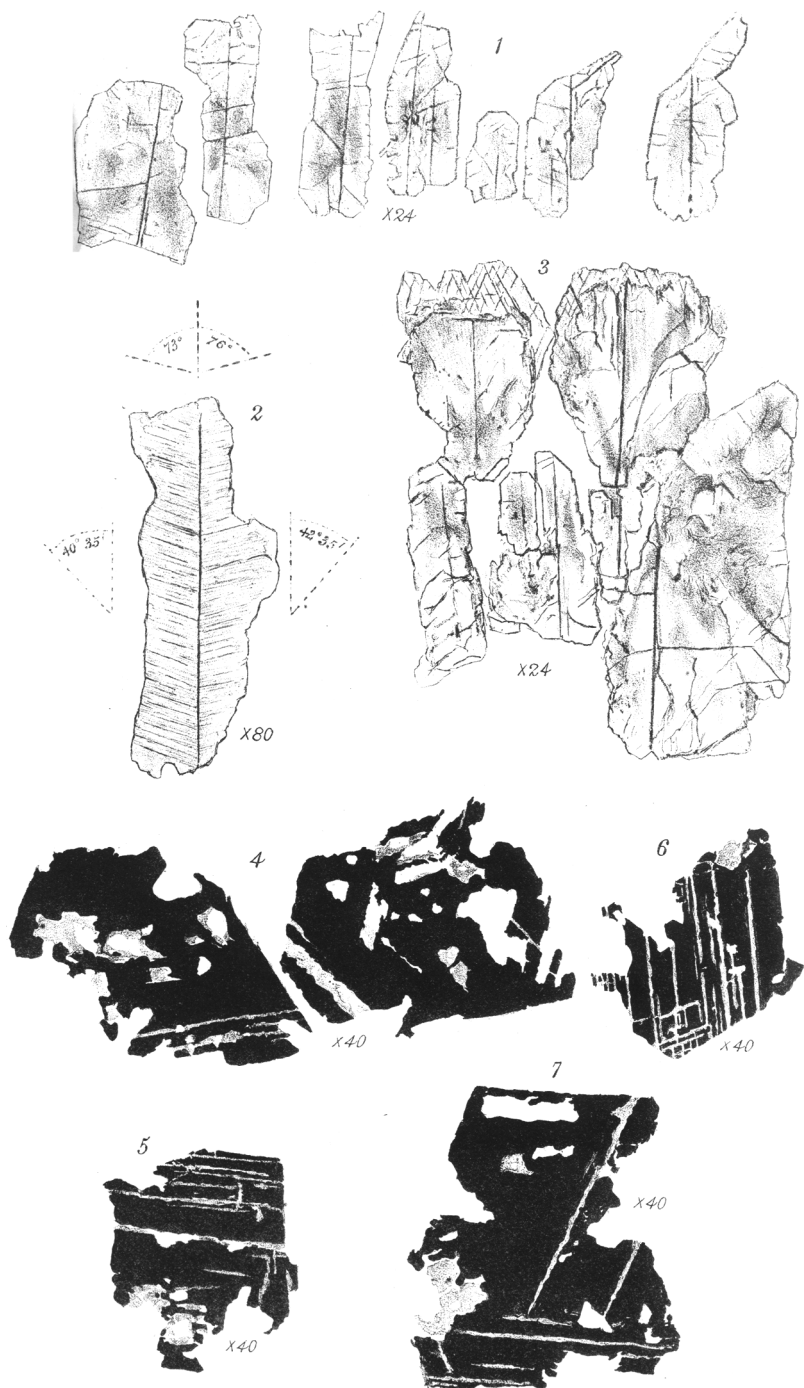
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- BOYD, E. F. On a part of the Carboniferous or Mountain Limestone Series of Northumberland. Trans. North of England Inst. of Engineering, vol. ix. p. 185. 1861.
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- . History of Alnwick, p. 469. 1869. Also papers in Proc. Ber. Field-Club and Trans. Tyneside Nat. Hist. Field-Club.
- ALLPORT, G. On the Microscopic Structure and Composition of British Carboniferous Dolerites. Q. J. G. S. vol. xxx. p. 552. 1874.
- CLOUGH, C. T. The Section at High Force, Teesdale. Q. J. G. S. vol. xxxii. p. 466. 1876.
- . The Whin Sill of Teesdale as an assimilator of the surrounding Beds *. Geol. Mag. decade 2, vol. vii. p. 433. 1880.

* This paper contains the following two analyses of the rock of the Whin Sill, made in Dr. Percy's Laboratory, which I quote for comparison with my own, given in the body of the present paper:—

| | I. | II. |
|--------------------------------------|--------|--------|
| SiO ₂ | 51.47 | 50.35 |
| Al ₂ O ₃ | 16.48 | 16.80 |
| Fe ₂ O ₃ | 3.61 | 3.51 |
| FeO | 8.49 | 8.36 |
| MnO | 0.46 | 0.41 |
| CaO | 8.22 | 9.01 |
| MgO | 5.10 | 5.73 |
| K ₂ O | 3.28 | 2.87 |
| Na ₂ O | 1.18 | 1.07 |
| FeS ₂ | .17 | .08 |
| H ₂ O | 1.70 | 2.00 |
| | 100.16 | 100.19 |
| Sp.Gr. | 2.82 | 2.84 |

I. From Tinkler's Syke, top of Widdy Bank Fell.

II. From Teward's Bridge, near Forest Church. TiO₂ was not estimated



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- TOPLEY and LEBOUR. On the intrusive Character of the Whin Sill of Northumberland. Q. J. G. S. vol. xxxiii. p. 406. 1877.
LEBOUR and FRYAR. On the Harkess Rocks near Bamburgh. Trans. N. of England Inst. of Engineering, vol. xxvi. 1877.
LEBOUR. Outlines of the Geology of Northumberland. Newcastle, 1878.
——. Geological Map of the County of Northumberland.
BONNEY, T. G. New Theory of the Formation of Basalt. Proc. Geol. Assoc. vol. vii. p. 104.

THE term Whin Sill is applied in the north of England to the intrusive sheet of basic igneous rock which forms such a marked feature in certain portions of the Lower Carboniferous district of Durham, Cumberland, and Northumberland. It is unnecessary, on the present occasion, to describe the stratigraphical relations of the rock, because full details are to be found in the papers cited above, and especially in those by Prof. Sedgwick and Messrs. Topley and Lebour. For some time there was a discussion as to whether the rock was intrusive or interbedded, but this discussion may be regarded as having been closed by the publication of the able paper by Messrs. Topley and Lebour. It is now admitted on all hands to be intrusive. To give some idea of its extent, I may mention that it is exposed as an inlier in Teesdale for a distance of many miles. It reappears in the Cross-Fell escarpment in Cumberland, and may be traced thence, with slight interruptions, across the county of Northumberland, to the sea-coast at Dunstanburgh, following in a general way the strike of the beds with which it is associated. As the strike bends round to the N.W. in the northern portion of Northumberland, the Whin Sill reappears on the coast at Bamburgh, and may be traced from this point to Kylloe, where it is last seen.

The distance from the point in the Cross-Fell escarpment, where it first appears, to Dunstanburgh is about 60 or 70 miles. Speaking of its development in Northumberland, Prof. Lebour says * :—" Its thickness varies very greatly, being scarcely 20 feet in places, and 150 feet in others. On an average it is from 80 to 100 feet thick." Inasmuch as the outcrop follows on the whole the strike of the beds, we may reasonably infer that the horizontal extension of the sheet is very great, amounting, in all probability, to hundreds of square miles, and that it underlies a large portion of the counties of Durham and Northumberland. It is an unfortunate circumstance that we are unable to speak definitely as to the period of its eruption. It is later than the Lower Carboniferous, and earlier than most of the faults of the district †; but whether it is pre-Permian or post-Permian must remain, for the present, an open question. It would be a very curious circumstance if the Whin Sill should prove to be contemporaneous with the diabase of the Eastern States

in these analyses and was therefore weighed in part with the SiO_2 , and in part with the Al_2O_3 and Fe_2O_3 . The excess of potash over soda is a remarkable feature in these analyses.

* Outlines of the Geology of Northumberland, p. 55.

† "Intrusive Character of the Whin Sill," Topley and Lebour, Quart. Journ. Geol. Soc. vol. xxxiii. p. 418.

of North America, which it so closely resembles in its petrological character and mode of occurrence.

The object of this communication is to describe the chemical and microscopical characters of the rock of the Whin Sill. The observations are based on specimens collected by myself, at many points in Durham, including Middleton, High Force, and Cauldron Snout; at a point about half a mile south of the locality marked Tyne Head on the Ordnance Map (Alston Sheet); and at Hot Bank, near Crag Lough, Bourgovicus, Bamburgh Castle, and many other points in Northumberland. Mr. Comozenski, the borough engineer of North Shields, kindly supplied me with specimens from Greenhead near Haltwhistle, Longhoughton and Little Mill near Alnwick, and Barrasford on the North Tyne. I have also examined the Little Whin Sill of Weardale, which occurs at a somewhat higher horizon than the Great Whin Sill of Teesdale. It is identical in its petrological characters with the latter rock. It will thus be seen that material has been collected from a sufficiently wide area to justify general conclusions as to the character of the rock, although it cannot be expected that all varieties have been observed. In no case are there any marked variations from the common type except such as depend, in all probability, on rapidity of cooling, and these may generally be found in one and the same locality.

There is one aspect of the question to which I have paid scarcely any attention, although it is one of great interest and importance; I refer to the phenomena of contact-metamorphism. This metamorphism is most marked in many cases, both at the upper and lower junctions. Limestones have become crystalline, and the shales have been converted into a kind of porcellanite, with development of garnet and other minerals.

The subject has been referred to by Prof. Sedgwick, Mr. Clough, and other writers; but it would well repay further investigation, with both the microscope and the chemical balance*.

PETROLOGICAL CHARACTERS.

The rock is dark grey or bluish grey when freshly exposed. In texture it varies from compact to coarsely crystalline, the most common variety being one in which the individual constituents are just recognizable by the naked eye. The compact variety occurs

* The following papers contain important observations on the contact-metamorphism produced by rocks similar in character to the Whin Sill:—

LOSSEN. Metamorphische Schichten aus der paläozoischen Schichtenfolge des Ost Harzes. Z. D. G. G. 1869, p. 281.

——. Ueber den Spilosit und Desmoisit Zinckens. Z. D. G. G. 1872, p. 701.

KAYSER. Ueber die Contactmetamorphosen der körnigen Diabase im Hartz, Z. D. G. G. 1870, p. 103.

SCHENCK. Die Diabase des oberen Ruhrthals und ihre Contacterscheinungen. (Inaugural Dissertation.) Bonn, 1884.

The work of these authors appears to establish the important fact that the metamorphism is accompanied by an actual transfer of felspar substance from the magma of the diabase to the surrounding rock.

only at the junctions, and is never more than a few inches in thickness. It is especially interesting because it exhibits a very distinct type of micro-structure. The coarse-grained varieties occur only where the rock attains a very considerable development, as, for instance, at Cauldron Snout. There is one very remarkable variety in which crystals of pyroxene measuring an inch in length are by no means uncommon. I have observed it in two localities, viz. half a mile south of Tyne Head and at Cauldron Snout. It occurs in the form of irregular masses in the coarser varieties of normal whin. Speaking of this variety, Prof. Sedgwick says* :—“Among the hard and almost indestructible masses there may be found a few concretions or irregular veins of a much coarser and more decomposing variety of rock in which the crystals of pyroxene are large and abundant. This mineral in such cases often puts on the form of irregular prisms or lengthened tabular crystals, the planes of which are bent and undulating.” Mr. Phillips examined these long crystals for Prof. Sedgwick, and ascertained “that they cleave easiest parallel to the plane P [∞ P Naumann], which is uncommon, and that the broad surfaces of the long crystals are not primary planes but represent the plane h [∞ P ∞ Naumann].” These determinations of Mr. Phillips will be verified later on. The junctions between the very coarse rock here referred to and the more normal whin are remarkably abrupt, notwithstanding the fact that the two varieties have the same mineralogical composition.

If we leave out of account one or two exceptional varieties, the statement holds good that the rock of the Whin Sill is remarkably uniform in general aspect. Its specific gravity is also fairly constant, as will be seen by the following list of determinations† :—

| | |
|---|-------|
| Hot Bank near Crag Lough | 2.924 |
| Longhoughton near Alnwick | 2.906 |
| Greenhead Quarry near Haltwhistle | 2.945 |
| Barrasford Quarry, N. Tyne..... | 2.945 |
| Crags near Bourgovicus | 2.944 |
| Middleton in Teesdale | 2.959 |

Amygdaloidal varieties are not common, and where they do occur, as at the Harkess Rocks near Bamburgh, they are associated with other peculiarities which lead one to suspect that the rock has consolidated under conditions somewhat different from those which prevailed during the formation of the normal whin.

The only constituents distinctly recognizable with the naked eye or with the hand-lens are pyroxene, a light-coloured substance which is presumably either felspar or the result of its alteration, and a few specks of pyrites. Under the microscope a much longer list of minerals can be made out. The essential constituents are seen to comprise plagioclase of one or more species, and generally more or

* Cambr. Phil. Trans. vol. ii. 166.

† Mr. Clough (Geol. Mag. dec. II. vol. vii. p. 442), gives the Sp. Gr. of a specimen from Tinkler's Syke as 2.82, and that of another from Teward's Bridge, near Forest Church, as 2.84.

less altered, a monoclinic pyroxene having certain special characters hereafter to be described, and titaniferous magnetic iron-ore. In the coarser-grained varieties quartz may always be detected as an original, and probably also as a secondary, mineral. The original quartz is intergrown with feldspar so as to produce the micro-pegmatitic structure of Lévy and Fouqué, or the granophyric structure of Rosenbusch. This micro-pegmatite plays the rôle of ground-mass, that is, it occurs between the interstices of the lath-shaped feldspars. If a series of sections cut from rocks which vary in the size of the constituent minerals be examined, it will be seen that the micro-pegmatitic structure in the interstitial matter becomes less and less pronounced as the finer-grained varieties are observed, until at last it is incapable of definite recognition; all that one then sees with the highest powers is an indistinct parallel fibrous structure. It is extremely interesting to trace this micro-pegmatite into a substance in which the minerals quartz and feldspar are incapable of recognition by the aid of the microscope, but in which there is reason to believe that they exist.

Apatite can always be detected, though only in very small quantity.

The accessory minerals, or those which do not always occur in the thin sections, include a rhombic pyroxene, a colourless monoclinic pyroxene—the so-called *salit* of many authors—brown hornblende, mica, pyrite, calcite, and various green decomposition-products. Before proceeding to describe the characters of the individual constituents it will be well to say a few words about the general microscopic structure of the different varieties.

The compact rock which forms, in many cases, the actual junction, and which may be well seen at both the upper and under surfaces of the Whin Sill in the neighbourhood of Cauldron Snout, shows a micro-porphyrific structure. Small, more or less lath-shaped sections of feldspar lie imbedded in a ground-mass, which is a veritable “*Mikrolithenfilz*,” composed of minute and evenly distributed specks of opaque iron-oxide and somewhat ill-defined and extremely small colourless microlites. In the thinnest preparations these microlites are seen superposed on each other, so that it becomes impossible to speak with certainty as to the presence or absence of any isotropic glass. It is impossible to look at this ground-mass and not be struck with its resemblance to the ground-mass of many andesites and porphyrites.

The finely crystalline rock which occurs a foot or two from the junction presents a very different type of micro-structure. It appears at the first glance to be holocrystalline, and to consist of crippled augite granules, lath-shaped feldspars, and grains of opaque iron-ore. On closer examination an extremely minute quantity of interstitial matter may generally be detected between some of the lath-shaped feldspars.

The medium-grained rock which makes up the main mass of the Whin Sill differs from the above merely in the extent to which the individual constituents have developed. Instead of the crippled

augite grains one now recognizes collections of such grains, and also definite crystalline plates into which the lath-shaped feldspars frequently penetrate. In short the rock possesses the "ophitic structure" of Messrs. Lévy and Fouqué. The interstitial matter becomes more pronounced and takes on here and there the micropegmatitic structure. In the coarser-grained varieties both the ophitic and micropegmatitic structures become more and more developed, and the dominant pyroxene shows a peculiar striated appearance, which will be described more fully in another part of this paper. In the coarsest variety of rock the pyroxene is developed in the form of long and somewhat flattened prisms and the micropegmatitic structure is most strikingly shown. Having described the general types of micro- and macro-structure, it will now be advisable to consider the individual minerals.

Feldspar.—This is probably, in all cases, the most abundant mineral. In the vast majority of cases only one generation can be detected. In three specimens, however, taken from Little Mill near Alnwick, Middleton in Teesdale, and Barrasford on the North Tyne, in addition to the prevailing feldspars which give lath-shaped sections, a larger feldspar, which is more evenly developed in the different directions, and which contains a nucleus with irregular ramifying inclusions, may be recognized. This evidently belongs to an earlier period of consolidation, and the rock is therefore not strictly granular in the sense in which that term is used by Rosenbusch *. The prevailing feldspar, as already indicated, gives lath-shaped sections. When fresh it shows the fine striation of plagioclase. Whether it belongs to one or more species I am not able to determine with any degree of confidence. The extinction-angles referred to the twinning-plane are not large. In the majority of cases the feldspar is more or less altered; and this alteration appears to affect all the individuals alike, a fact which tells in favour of the view that we are here dealing with a single species. For the purpose of isolating the different constituents a specimen of a moderately coarse-grained variety of the normal whin was broken up in an iron mortar, and the fragments passed through a series of sieves. The grains selected for further treatment were those which passed through a sieve having 50 meshes to the inch and were stopped by one having 100 meshes. These grains were so small as to consist, in a large measure, of the individual constituents of the rock. They were washed to remove the fine powder, dried and then placed in the Sonstadt solution having a specific gravity of about 3. The grains of pyroxene and titaniferous magnetic iron sank to the bottom, whereas the grains of feldspar substance and many others of a composite character remained suspended. The grains of pyroxene and magnetic iron-ore were separated for further treatment, and then the solution was diluted down gradually. It was found that the feldspar substance remained suspended in a solution of 2·70, and sank in one of 2·67. The grains which fell as the solution was diluted from 2·70 to 2·67

* "Ueber das Wesen der körnigen und porphyrischen Structur bei Massengesteinen," Neues Jahrbuch, Band ii. 1882.

were separated from the rest and analyzed with the following result:—

| | |
|--------------------------------------|-------|
| SiO ₂ | 61·18 |
| Al ₂ O ₃ | 19·95 |
| Fe ₂ O ₃ | 3·20 |
| CaO | 5·45 |
| MgO | ·92 |
| K ₂ O | 2·83 |
| Na ₂ O | 4·70 |
| H ₂ O | 1·13 |
| | <hr/> |
| | 99·36 |

Both microscopic and chemical analysis shows that we are not dealing with pure felspar substance, but a mixture of quartz, felspar, and decomposition-products.

The molecular ratio of Na(K):Ca, according to the analysis, is 2·18:1; but we must remember that some lime has been removed from the rock. Nevertheless, by introducing the most favourable assumption as to the amount of lime which has been removed, we cannot make the ratio of Na(K):Ca so low as 1:1, and we seem therefore driven to the conclusion that in the original felspar substance, whether it consisted of one or more species, this ratio agreed approximately with that of andesine. The large amount of K₂O may imply the existence of an independent potash felspar; but of this I am not able to give any definite microscopic evidence, and we must remember that some andesines are supposed to contain as much as 2 or 3* per cent. of this substance.

The dominant Pyroxene.—This mineral, in the thin sections and in a perfectly fresh condition, appears to be of a pale brown colour. In the finer-grained varieties it occurs in the form of grains, and in the coarser varieties either as grains or irregular plates. The usual prismatic cleavages are common, and twinning may not unfrequently be observed. External crystalline boundaries are, as a rule, absent. In the large irregular plates a fine striation may frequently be observed. This, however, is by no means a constant feature. In the freshest rock specimens it is absent; in the most altered specimens it is universally present where the pyroxenes attain any considerable size. Some sections of pyroxene show it in certain parts and not in others. It seems impossible therefore to avoid the conclusion that this structure is of secondary origin.

It reminds one at once of the corresponding structure in diallage; and an interesting question arises as to whether we are here dealing with true diallage—that is, with a pyroxene having a laminated structure parallel to $\alpha \bar{P} \alpha$ —or with some other modification of augite. It has already been pointed out that in the coarsest variety of whin the pyroxene is developed in the form of elongated prisms, with more or less definite crystalline faces. If, then, this variety

* Rammeisburg, 'Handbuch der Mineral-Chemie,' Band ii. pp. 569–570.

shows the same striation, and we can identify the crystalline faces, it will furnish us with the means of determining this point.

Looking at a fractured surface of this extremely coarse-grained rock, one sees long bright black cleavage-faces, measuring, say from 2 to 3 centimetres in length, and from 1 to 3 millimetres in breadth. These are traversed by a fine striation, which runs at right angles to the length of the face, and which can be readily seen with a hand-lens. These faces represent the orthopinacoid, according to the determinations of Phillips. If, now, we break the specimen so as to obtain an end view of the prism, we see that it is bounded by two small faces which have a bronzy lustre, similar to that of diallage, and which are inclined at approximately the same angle as the basal planes in a crystal of augite twinned on the normal plan. We see, further, that a number of similarly twinned crystals are placed close to each other, with corresponding faces parallel. Now these small bronzy-looking faces are the basal planes of the crystals according to the determinations of Phillips, and they are also the planes of easiest cleavage. Owing to the size of the crystals it is easy to prepare sections in definite directions for microscopical and optical examination. Such sections establish conclusively the correctness of Mr. Phillips's determinations. Those cut parallel to the long black lustrous faces ($\infty P \infty$) give straight extinction, and show a marked striation at right angles to the vertical axis; those cut at right angles to this axis (Pl. XXIX. fig. 1) show that the prisms are formed almost entirely of the ortho- and clino-pinacoids (the prismatic faces only appear as slight truncations), and that each individual is twinned in such a way that the face of composition is at right angles to the plane of the optic axes; that is according to the normal type. These sections also show that whereas the prismatic cleavages are well seen in the fresh crystals or portions of a crystal, they are obscure wherever alteration has taken place. Other and somewhat irregular cleavages parallel to the two vertical pinacoids, especially the clino-pinacoid, may be observed. Sections cut parallel to the latter pinacoid (fig. 2) show an oblique striation, the striæ making with the twinning-line an angle of about 75° , *i. e.* the angle β (Naumann) of augite. In these sections the angle of extinction referred to the twinning-line is 42° . The facts mentioned above prove conclusively that the striation so frequently referred to is due to lamination parallel to ∞P and not to $\infty P \infty$. The mineral therefore is not true diallage. That the striation observed in the pyroxene of the normal whin is of a similar character can be easily proved by the application of optical tests to the thin sections. We have now to deal with the chemical composition of this pyroxene.

In a former part of this paper (p. 645) the method of separating the pyroxene and titaniferous iron-ore from the felspar and quartz was explained. The two former minerals were separated from each other by means of a small bar-magnet. It was found that the iron-ore could be entirely extracted in this way. The pyroxene grains, after having been roughly sorted under the microscope, were analyzed, with the following result. They were not perfectly pure, for it was

found impossible to remove all traces of the felspar, owing to the intimate manner in which it was intergrown with the augite.

Monoclinic pyroxene, Cauldron Snout, from a moderately coarse-grained rock (sp. gr. about 3.30):—

| | Comp. | Mol. Rel. |
|--|-------|-----------|
| SiO ₂ | 49.03 | 8182 |
| Al ₂ O ₃ | 5.46 | 533 |
| FeO | 15.57 | 2167 |
| MnO | .22 | 31 |
| CaO | 15.34 | 2746 |
| MgO | 11.66 | 2922 |
| Na ₂ O (K ₂ O) . | 1.24 | 200 |
| H ₂ O | .81 | |
| | 99.33 | |

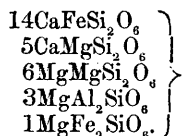
A portion of the alkalis and alumina in this analysis may certainly be referred to felspar. The total iron is reckoned as FeO. The most striking feature is the large excess in the number of molecules of Fe+Mg over the number of molecules of Ca. This cannot possibly be explained on the assumption that a visible mixture of two pyroxenes was analyzed, for care was taken to select a rock in which the rhombic mineral could not be recognized. To determine if possible somewhat more accurately the composition of the prevailing pyroxene, an isolation of the mineral from the coarsest variety of Whin Sill was effected. The greatest care was exercised, and every grain used in the analysis was passed before the eye under the microscope.

| | I. | II. | III. | IV. | |
|---|-------------|-------|-------|------|------|
| SiO ₂ | 50.71 | 50.21 | 48.41 | 8079 | 54.2 |
| Al ₂ O ₃ | 3.55 | 3.24 | 4.05 | 395 | 2.6 |
| Fe ₂ O ₃ | | | 2.36 | 149 | 1.0 |
| FeO..... | 15.30 | 17.40 | 15.08 | 2099 | 14.0 |
| MnO | 0.81 | | .37 | 52 | .3 |
| CaO | 13.35 | 13.92 | 15.98 | 2860 | 19.1 |
| MgO | 13.63 | 14.05 | 12.14 | 3043 | 20.4 |
| Na ₂ O (K ₂ O) .. | 1.48 | | | | |
| H ₂ O..... | 1.17 (loss) | | 1.19 | | |
| | 100.00 | 98.82 | 99.58 | | |

- I. Pyroxene from West Rock, Newhaven, Connecticut. American Journal of Science, 1875, p. 185. W. Hawes on the Trap rocks of the Connecticut Valley.
- II. Striated pyroxene isolated from a basaltic rock from Kølter, Farøe Islands. Dr. A. Osann, "Ueber einige basaltische Gesteine der Färøer," Neues Jahrbuch, 1884, Band i. p. 48.
- III. Striated pyroxene from the coarsest variety of the Whin Sill, $\frac{1}{2}$ m. south of Tyne Head. Sp. gr. 3.33 (approximately).
- IV. Molecular relations of III.

In our pyroxene R:Si=1:1. R:R=1:14.8. Ca:Mg:Fe=

1·36:1·45:1. If we adopt the view of Tschermak and Dölter*, and regard the pyroxenes as isomorphous mixtures of double salts in which the sesquioxide bases are present in a silicate of the form RRSiO_6 , then we may represent the composition of this mineral approximately by the formula—



This formula corresponds to the following percentage composition:—

| | |
|-------------------------------|-------|
| SiO_2 | 48·97 |
| Al_2O_3 | 4·65 |
| Fe_2O_3 | 2·41 |
| FeO | 15·23 |
| CaO | 16·06 |
| MgO | 12·68 |

100·00

The mineral is remarkable for the large amount of iron, existing presumably in a silicate of the Hedenbergite type, and for the excess of magnesia over that required to combine with the remaining lime and the sesquioxide bases. This excess implies the existence of the silicate MgSiO_3 , written in the formula as $\text{MgMgSi}_2\text{O}_6$ for the sake of symmetry. Whatever theory we adopt as to the constitution of the pyroxenes, we seem driven to the conclusion that this silicate, known to us as the rhombic mineral, enstatite, exists in a monoclinic augite. One point is certain, viz. that the substance analyzed did not consist of a visible mixture of rhombic and monoclinic pyroxene. The mineral was uniform in appearance and in optical properties.

The point here raised is one of considerable interest, for two reasons—firstly, as bearing on the general question of isomorphism; and, secondly, because in other varieties of the Whin Sill a rhombic pyroxene occurs as an accessory constituent, and, in some cases, may even be observed intergrown with the monoclinic mineral in such a way as to show that its position was governed by general laws of crystalline growth. We know that the most powerful object-glasses do not enable us to approach the limits of molecular structure, and there is therefore no reason to believe that the microscopic limit of visibility corresponds with anything definite in the nature of crystalline growth. The intergrowth of two minerals which can be frequently observed may quite well take place on so small a scale as not to be capable of recognition; indeed we have in this paper traced micro-pegmatite† down to a substance in which

* "Ueber die Constitution der Pyroxengruppe" von C. Dölter, Tschermak's Mith. Neue Folge, Band ii. p. 193. See also numerous other papers by the same author in the same journal.

† Consider also the case of perthite and micro-perthite.

the definite structure cannot be recognized, but in which there is every reason to believe that it actually exists. Is it possible that the mineral now under consideration is a submicroscopic association of monoclinic and rhombic pyroxene? The idea here thrown out was suggested to me in conversation by Prof. Rosenbusch.

Returning once more to the general consideration of the pyroxene, we observe that, so far as the ratios Ca : Mg : Fe are concerned, it is intimately connected with the pyroxene of the Connecticut diabase and with that of a basaltic rock from the Farøe Islands. Both these pyroxenes show the same tendency to develop a laminated structure parallel to ∞P . To what extent this tendency is connected with the composition I am, of course, unable to state. Two other points require attention. The ratio of R : R is greater in the Tyne-Head pyroxene than in that of the other two localities, and the amount of water is considerable. It is possible that the development of the laminated structure is connected with the addition of water. Thus the pyroxene of the Cauldron-Snout rock is less conspicuously laminated than that of the rock from Tyne Head, and it contains less water. A comparison of the two analyses of the Whin-Sill pyroxene shows that the coarse variety is closely allied to, though not identical with, the common rock-forming mineral.

Opaque Iron Oxide.—In the compact varieties, this substance occurs in the form of extremely minute specks, evenly scattered throughout the section. In the finely crystalline varieties it occurs in the form of grains, and in the coarse varieties in the form of extremely irregular ragged masses. Many of the sections, however, show forms which are supposed to indicate ilmenite (Pl. XXIX. figs. 4, 5, 6, and 7), and the white alteration produced may often be observed. All the grains, which consist either wholly or in part of the opaque iron-ore, may be extracted from the powder by a weak bar-magnet. True ilmenite is not attracted by a strong electro-magnet. Owing to the extremely ragged character of this titaniferous ore, the grains extracted by the method above referred to are largely composed of felspar and augite. An attempt was made to purify the substance by treatment with hydrofluoric acid, but the result was unsatisfactory, as the substance itself was more or less decomposed with separation of titanie acid. An analysis of the impure substance yielded the following result:—

| | |
|--------------------------------------|-------------|
| SiO ₂ | 12.16 |
| TiO ₂ | 24.51 |
| Al ₂ O ₃ | 3.36 |
| Fe ₂ O ₃ | 24.70 |
| FeO | 26.54 |
| CaO | 4.40 |
| MgO | 1.49 |
| | <hr/> 97.16 |

This analysis leaves much to be desired; still it will give some idea of the composition of the ore. Since augite occurs as a visible impurity, we shall probably not err seriously if we assume that the magnesia is wholly present in that mineral. Deducting, then, an

amount of iron oxide which corresponds to 1·49 per cent. of MgO , and assuming that the remaining iron is wholly associated with TiO_2 to form the magnetic ore, we have the composition of this ore as follows:—

| | | | Mol. Rel. |
|-------------------------|------------|--------|-----------|
| TiO_2 | 24·51 | 33·30 | 4162 |
| Fe_2O_3 | .. 24·70 | 33·56 | 2101 |
| FeO | 24·39 | 33·14 | 4611 |
| | 73·60 | 100·00 | |

Another sample from the same rock was partially analyzed. ·6150 gramme gave ·1635 gramme TiO_2 , and ·3639 gramme Fe_2O_3 (total iron). If we assume that the total Fe is associated with TiO_2 to form ilmenite ($\text{FeO TiO}_2 + n\text{Fe}_2\text{O}_3$), then we have as the composition of the mineral—

| | |
|-------------------------|-------------|
| TiO_2 | 31·99 |
| FeO | 28·72 |
| Fe_2O_3 | 39·29 |
| | 100·00 |

These results can of course only be regarded as rough approximations to the truth. In the second case no determination of FeO was made. In the first case this was done, and the result shows that there is more FeO than is required to form the compound FeOTiO_2 —that is, more than is required for true ilmenite.

The analysis and also the physical properties of this substance agree with the assumption that we are here dealing with a mixture of magnetite and ilmenite, and the question arises—Is there any evidence that these two minerals occur intergrown together? Such evidence is supplied by the work of Renard and De la Vallée Poussin*, Neef†, and Küch‡. Neef found, on treating a certain section of diabase with hot hydrochloric acid, that the opaque iron-ore was only partially destroyed; a fine network, due to two parallel series of lamellæ of ilmenite intergrown so that the angles between the lamellæ corresponded to the angles of the fundamental rhombohedron of ilmenite, remaining behind. The mineral removed was no doubt magnetite, as this substance is much more readily attacked by hot hydrochloric acid than ilmenite. Küch obtained precisely similar results in the case of a rock from West Africa. Renard and De la Vallée Poussin figure such a network as that referred to in plate i. fig. 6, of the work cited below. Lastly, the alteration of the Whin-Sill substance into leucoxene takes place along two sets of parallel planes (see Pl. XXIX. figs. 4, 5, and 6). We may conclude, therefore, that we are here dealing not with one definite mineral, but with an intergrowth of two, viz. magnetite and ilmenite.

It is not a little interesting to observe that we have in this rock three separate instances of the intergrowth of two minerals, viz.

* "Mémoire sur les roches dites plutoniennes de la Belgique et de l'Ardenne française." Mémoires couronnés de l'Académie Royale de Belgique. Tome xl. p. 50.

† "Ueber seltenere krystallinische Diluvium-Geschiebe der Marke," Z. D. G. G. xxxiv. p. 470.

‡ "Beitrag zur Petrographie des west-africanischen Schiefergebirges." Min. Mitth. Neue Folge, vi. p. 129.

quartz and felspar, a monoclinic and a rhombic pyroxene, and magnetite and ilmenite.

Rhombic Pyroxene.—This mineral is by no means uniformly present, but where it does occur several sections may usually be recognized in the same microscopic preparation. In its most typical development it takes on the form of elongated prisms, and shows a much more decided approach to crystalline form than the prevailing monoclinic pyroxene. Two terminal faces meeting at an obtuse angle may sometimes be detected. In the fresh condition this mineral appears nearly colourless when examined by ordinary light. It develops a fibrous structure parallel with the long axis of the prism by alteration, and finally passes over into a green serpentinous substance. Examined with a polarizer only, the longitudinal sections show a decided pleochroism, appearing colourless or of an extremely pale green when the long axis of the prism corresponds with the short diagonal of the nicol, and of a pale brown or reddish brown when the opposite relation holds. Longitudinal sections generally show irregular transverse cracks, and invariably give straight extinction. Another and a very characteristic feature is the low order of the interference-colours under crossed nicols. In sections in which the augite constantly gives the brilliant pinks and greens of the second and third orders of Newton's scale, the rhombic pyroxene gives the pale tints of the first order. In a section taken from a Middleton specimen I have observed intergrowths of the augite and the rhombic mineral. Thus, one crystal of augite cut approximately parallel to the clinopinacoid, shows a thin lamella of rhombic pyroxene in its centre. The latter mineral gives straight extinction, and polarizes in the pale yellow of the first order; the former mineral extinguishes at an angle of 43° , and polarizes in the brilliant green of the third order*. In another portion of the same slide two thin lamellæ of augite are seen to be enclosed in a good-sized crystal of the rhombic pyroxene.

What name is to be applied to this mineral? In the absence of more direct optical or chemical evidence the properties of colour and pleochroism are the only ones available for the purpose of distinguishing between enstatite, bronzite, and hypersthene. Typical enstatite appears devoid of pleochroism. Bronzite is slightly and hypersthene markedly pleochroic in thin sections. In other words, the depth of colour and the intensity of pleochroism increase with the amount of iron. Now the pleochroism of the mineral in question is decided, though much less marked than that of the hypersthene of the andesites, and therefore the term bronzite seems to be the most applicable. It must be admitted, however, that we want a general term for the rhombic pyroxenes which are now being recognized in so many rocks, and which are incapable of precise determination. Prof. Rosenbusch uses the term "Enstatite" to cover the entire group. Prof. Tschermak † and Dr. F. Becke ‡ on the

* The quartz wedge described by Sorby in the 'Monthly Microscopical Journal,' 1877, p. 209, was used for these determinations.

† Lehrbuch der Mineralogie, 1854, p. 436.

‡ "Ueber die Unterscheidung von Augit und Bronzit in Dünnschliffen." Min. Mitth. Band v. 1883, p. 527.

other hand use the term "Bronzite." There is therefore at present no general agreement on this point, and inasmuch as the test of pleochroism seems to show that the mineral of the Whin Sill is intermediate between enstatite and hypersthene, the term bronzite will probably not be considered inappropriate.

Colourless monoclinic Pyroxene.—In his paper on Swedish diabases Törnebohm* describes a colourless monoclinic mineral which he regards as a lime-magnesia bisilicate, and to which he gives the name Salit. It is distinguished from the prevailing pyroxene by the absence of colour, by the presence of more definite crystalline boundaries, and by its easy alterability. In a few specimens of the Whin Sill I have observed a colourless monoclinic augite which may possibly be this mineral. It appears to be developed in the form of long slender prisms. Cross-sections show the forms ∞P , $\infty P \bar{\infty}$, and $\infty P \bar{\infty}$, the pinacoids predominating just as in the exceptional variety of the common pyroxene above described. The individuals are, moreover, invariably twinned. I feel some doubt as to whether this is not, after all, a variety of the common pyroxene, which in the fresh condition and in a very thin section is frequently almost colourless.

Hornblende.—This mineral is often present in small quantity. It never occurs as an independent mineral, but is always attached to the augite, from which it may be distinguished by its deep brown colour, its cleavages, and its pleochroism. The usual mode of occurrence is in the form of small irregular patches on the margin of the augite. The boundary between the augite and the hornblende is abrupt but not sharp. The external boundaries of the hornblende are frequently formed of definite crystalline faces, and they project beyond the natural boundaries of the augite (see Pl. XXIX. fig. 3). The relation therefore of the brown hornblende to the augite is not such as we should expect if the former mineral were produced from the latter by a process of paramorphic change.

Mica.—A brown mica may occasionally be detected. It is by no means common, and when it does occur its characters are not such as to call for any special description.

Quartz.—This substance occurs in the form of crystalline grains, and also in the micro-pegmatite. In the latter case it is of primary origin; in the former it may be, and probably is in many cases, of secondary origin.

Apatite.—This occurs as definitely recognizable hexagonal prisms. Extremely long, thin, colourless needles are also abundant. These, I believe, are usually referred to apatite.

Chlorite and other green Alteration-products.—In most sections green fibrous minerals, resulting from the decomposition of the bisilicates, may be observed. These have not been subjected to any exhaustive examination.

Pyrite may be recognized both macroscopically and microscopically. It is extremely irregular both in form and distribution.

* Neues Jahrbuch, 1877, p. 263. Many of the characters which Törnebohm gives as distinctive of the salit would apply to the bronzite, especially those depending on alteration.

We have now to discuss the bulk-analysis of the rock. Two specimens were analyzed—one a moderately coarse-grained variety from Cauldron Snout, composed mainly of monoclinic pyroxene, felspar, magnetic iron-ore, and quartz, with a very small quantity of colourless pyroxene, but no trace of bronzite; the other a medium-grained rock from the crags near the Roman station of Bourgovicus, which contained both bronzite and the colourless pyroxene, in addition to the ordinary constituents. Both specimens were somewhat altered, the felspars having here and there lost their individual action on polarized light, and chloritic minerals having been slightly developed.

The fine powder of the rock was dried at 110°. The titanitic acid in I. was determined with special care.

For purposes of comparison I have placed two analyses of the Connecticut diabase, and one of a rock of similar character from Spitzbergen, side by side with my own analyses of the Whin Sill.

| | I. | II. | III. | IV. | V. |
|-----------------------------------|--------------|---------------|--------------|--------------|---------------|
| SiO ₂ .. | 51.22 | 50.71 | 51.78 | 52.68 | 49.78 |
| TiO ₂ .. | 2.42 | 1.92 | .. | .. | 2.97 |
| Al ₂ O ₃ .. | 14.06 | 14.78 | 14.20 | 14.14 | 14.05 |
| Fe ₂ O ₃ .. | 4.32 | 3.52 | 3.59 | 1.95 | 14.86 |
| FeO .. | 8.73 | 8.95 | 8.25 | 9.79 | .. |
| MnO .. | 0.16 | 0.31 | 0.44 | 0.44 | 0.13 |
| CaO .. | 8.33 | 8.21 | 10.70 | 9.38 | 9.44 |
| MgO .. | 4.42 | 5.90 | 7.63 | 6.38 | 5.65 |
| K ₂ O .. | 1.25 | 1.39 | 0.39 | 0.87 | } 1.70 |
| Na ₂ O .. | 2.55 | 2.76 | 2.14 | 2.56 | |
| H ₂ O .. | 1.28 | 1.78 | 0.63 (loss) | 1.60 (loss) | .. |
| CO ₂ .. | 0.19 | 0.25 | .. | .. | .. |
| P ₂ O ₅ .. | 0.25 | .. | 0.14 | .. | .. |
| FeS ₂ .. | 0.49 | .. | .. | .. | .. |
| Loss .. | .. | .. | .. | .. | 1.42 |
| | <u>99.67</u> | <u>100.48</u> | <u>99.89</u> | <u>99.79</u> | <u>100.00</u> |
| Sp. Gr... | 2.98 | 2.944 | 3.03 | 2.97 | .. |

- I. Whin Sill. Cauldron Snout, Durham. Moderately coarse-grained variety.
- II. Whin Sill. Crags near Roman station of Bourgovicus, Northumberland.
- III. West Rock. W. of New Haven, Connecticut. Hawes, 'American Journal of Science,' 1875, p. 185.
- IV. Mount Holyoke, Massachusetts. Hawes.
- V. Diabase. Gänze Island, in the Eisfjord. 'Petrographisch-geologische Beobachtungen an der Westküste Spitzbergens,' Min. Mitth. Heft iv. 1874, p. 264.

If we assume that the magnesia in I. is wholly present in the monoclinic pyroxene (and microscopic examination shows that this assumption is very nearly correct, only a very small quantity of chlorite being present), we can then construct the following table,

* In all the original analyses contained in this paper the powder was first dried at 110° C.

MICROSCOPICAL CHARACTERS OF THE WHIN SILL.

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which represents quantitatively both the chemical and mineralogical composition of the rock :—

Table illustrating the Composition of a Specimen of the Whin Sill from Cauldron Snout, Durham.

| | SiO ₂ | TiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | FeO. | MnO. | CaO. | MgO. | K ₂ O. | Na ₂ O. | H ₂ O. | CO ₂ | P ₂ O ₅ | FeS ₂ | Total. |
|------------------------|------------------|------------------|--------------------------------|--------------------------------|-------|-------|-------|-------|-------------------|--------------------|-------------------|-----------------|-------------------------------|------------------|--------|
| Augite | 17.62 | ..... | 1.47 | 0.85 | 5.49 | 0.13 | 5.81 | 4.42 | ..... | ..... | 0.43 | ..... | ..... | ..... | 36.22 |
| Titaniferous ore ..... | ..... | 2.42 | ..... | 2.44 | 2.41 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 7.27 |
| Polish felspar | 4.78 | ..... | 1.36 | ..... | ..... | ..... | ..... | ..... | 1.25 | ..... | ..... | ..... | ..... | ..... | 7.39 |
| Soda felspar | 14.80 | ..... | 4.22 | ..... | ..... | ..... | ..... | ..... | ..... | 2.55 | ..... | ..... | ..... | ..... | 21.57 |
| Line felspar | 4.78 | ..... | 4.08 | ..... | ..... | ..... | 2.23 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 11.09 |
| Apatite ..... | ..... | ..... | ..... | ..... | ..... | ..... | 0.29 | ..... | ..... | ..... | ..... | ..... | 0.25 | ..... | 0.54 |
| Pyrites ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 0.19 | 0.49 |
| Remainder | 9.24 | ..... | 2.93 | 1.03 | 0.83 | 0.03 | ..... | ..... | ..... | ..... | 0.85 | 0.19 | ..... | ..... | 15.10 |
| Total | 51.22 | 2.42 | 14.06 | 4.32 | 8.73 | 0.16 | 8.33 | 4.42 | 1.25 | 2.55 | 1.28 | 0.19 | 0.25 | 0.49 | 99.67 |

The excess of alumina, iron, and water, and a portion of the excess of quartz, are no doubt due to the alteration which has taken place, kaolin and chlorite both being present. A large portion of the silica, however, no doubt represents free original quartz. If the felspar molecules were associated with each other to form a single mineral, the ratio of Na (K) : Ca would be, according to the above, 2.72 : 1. But lime has certainly been removed from the rock; and if we allow for this, on the basis that the excess of Al_2O_3 was wholly present in molecules of anorthite, then this would make the above ratio 1.58 : 1. The discussion of the bulk-analysis leads us, therefore, again to the conclusion that the original felspar, if of one species, was andesine.

We cannot construct a table for the Bourgovicus rock, because the microscope shows that both bronzite and the colourless pyroxene occur, in addition to the common pyroxene.

Relations of the Whin Sill to other Rocks.

If we compare the rock of the Whin Sill with the dykes described in my former paper (Q. J. G. S. vol. xl. p. 209), we are at once struck with its resemblance to those of Hett and High Green. The figure which is given of the rock of the High Green dyke (*l. c.* pl. xiii. fig. 2) represents faithfully the general structure of the Whin Sill. The ilmenite of my former paper is, no doubt, the same mineral as the titaniferous magnetic iron-ore of the present paper.

There are some very interesting points both of resemblance and difference between the Whin Sill and the eruptive rock of Penmaenmawr, described by Mr. J. A. Phillips (Q. J. G. S. vol. xxxiii. p. 423). These two rocks are composed of the same minerals, associated in very different proportions. Thus the freshest specimens of the Penmaenmawr rock are seen under the microscope to consist of bronzite*, monoclinic pyroxene with lamination parallel to ∞P , plagioclase, titaniferous iron ore, and quartz, both in the form of grains and associated with felspar in micro-pegmatite. In the Whin Sill the monoclinic pyroxene is largely in excess of the bronzite; but in the Penmaenmawr rock the reverse relation holds—the bronzite is very largely in excess. A comparison of the bulk-analyses shows that the Penmaenmawr rock possesses a larger proportion of felspar than the Whin Sill.

Comparing our rock with the Carboniferous dolerites of central England we are struck by the absence of olivine. I have not seen

* I think this is the mineral that Mr. Phillips referred to hornblende. I have not seen any hornblende in the rock, and at the time that Mr. Phillips's paper was written the methods of distinguishing the crystal-systems by reference to the extinction-angles was not well known. It is not surprising, therefore, that he should have taken the pleochroic bronzite for hornblende. I may state that my attention was specially directed to the Penmaenmawr rock by the following sentence in Rosenbusch's work, 'Die massige Gesteine,' p. 352:—"Die Trappe von Conway und von Penmaenmawr in Wales gehören zu den enstatitführenden Diabasen und zwar zu den typischsten Repräsentanten derselben."

a single instance of this mineral in the Whin Sill, although Mr. Allport mentions it as occurring in the rock from Ward's Hill *, near Rothbury.

Outside this country, the nearest allies to our rock that I can find are certain Swedish diabases described by Törnebohm †, and the great masses of trap which occur as dykes and intrusive sheets in the Triassic-Jurassic strata of the Eastern States of North America ‡. I have a good series of the American rocks from New Jersey and Connecticut, and both macroscopically and microscopically they are in many cases identical with the Whin Sill. In mode of occurrence and chemical composition there is also great similarity. Lime-felspar, however, appears to be more abundant in the American rocks. Dr. Hawes separated the felspar substance, extracted from a rock from Jersey City, into two portions, one having Sp. Gr. > 2.69, the other < 2.69. The former, on analysis, proved to be labradorite, the latter andesine.

It is not a little interesting to observe, near the opposite shores of the Atlantic, rocks with so many points of close resemblance.

EXPLANATION OF PLATE XXIX.

- Fig. 1. A row of twinned crystals of the dominant pyroxene, cut at right angles to the *c* axis, from a coarse variety of the Whin Sill near Tyne Head. The forms and mutual relations of the crystals are accurately represented. In the actual specimen the interspaces are filled with decomposed felspar and a little micro-pegmatite. If we speak of the sections as approximately rectangular for purposes of reference, then the optic axial plane lies parallel with the short side of the rectangle, which consequently represents the clinopinacoid. The long side of the rectangle is the ortho-pinacoid, and the prismatic faces are represented by the slight truncations of the angles. The crystals are seen to be twinned with the ortho-pinacoid for the face of composition. $\times 24$.
2. Section of twin crystal of the same pyroxene cut approximately parallel to the clinopinacoid. The striations of the two halves make with the twinning-line angles of 76° and 73° respectively. The mean of these is $74^\circ 30'$, and the angle β of augite, as given in Naumann-Zirkel's Mineralogie, is $74^\circ 11'$. The two halves extinguish at angles of $42^\circ 35'$ and $40^\circ 35'$ respectively. $\times 80$.
3. Sections of two imperfect pyroxenes with marginal hornblende. The external form of the hornblende and the characteristic cleavages are well shown. The minerals in contact with the hornblende are chlorite and quartz. $\times 24$.
- 4, 5, 6, 7 §. Forms of the magnetic titaniferous iron-oxide. The dotted spaces represent leucoxene. The mode of alteration reveals the structure of the substance. It consists of a framework of ilmenite lamellæ with the interspaces occupied by a different substance, probably magnetite. Middleton. $\times 40$.

* Quart. Journ. Geol. Soc. vol. xxx. p. 552.

† Neues Jahrbuch, 1877, p. 258.

‡ W. Hawes, "Trap Rocks of the Connecticut Valley," Amer. J. Science, 1875, p. 185.

§ From a section kindly lent by Prof. Lebour.