A contribution to the petrology of the Whin Sill.

(With Plates III and IV).

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Contents.

I. Introduction.

The 'Whin Sill' of the north of England is a classic example of an igneous intrusive sheet. A detailed account of its general tectonic and petrographic features has been the subject of a recent paper by A. Holmes and H. F. Harwood.[1] The present author has made the attempt not so much to give a complete account of the petrology of the Whin Sill, as to describe certain peculiar developments within its mass, such as the coarse-grained bands, acid segregations, &c.

II. Petrographical Description.

Although remarkably uniform in its petrographical characters and its chemical composition, the rock forming the sill can be subdivided into three main types or varieties:

(1) Fine-grained variety (basaltic type), occurring along the upper and lower contacts (cooling selvages). It passes rapidly into the

(2) Medium-grained variety (doleritic type), which is the normal and dominant type.

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

(3) Coarse-grained variety (gabbroid type) is of a remarkably coarse texture, occurring in the form of bands, segregation veins, and spheroids, always sharply separated from the normal rock. This variety is of comparatively rare occurrence and forms an extremely small proportion of the rock.

(1) *Fine-grained variety.*

The fine-grained variety (selvage) is produced by the rapid cooling of the intruded magma at the contact with the sedimentary rocks. It varies in texture from anchi-tachylytic to aphanitic. Numerous felspathic microlites together with a few augitic grains are embedded in a brownish semihyaline groundmass. Sometimes microphenocrysts of augite are present. Iron-ore is present in the form of fine skeletal grid-like aggregates of early crystallization and also in the form of small granules, sometimes moulded on felspar and augite. Occasionally we may observe small phenocrysts entirely transformed into an aggregate of serpentine and iron-ore, which suggests a former presence of olivine. These small and isolated phenocrysts may therefore be relics of an early crop of olivine, subsequently resorbed or partly autopneumatolized by the magma.

In certain places in the fine-grained, as well as in the medium-grained, variety small amygdules are found. They are usually composed of calcite, quartz, and chlorite. Often small spongy pyritic spheroids are found at the contact (usually at the contact with shales). In contact with limestone or marly shale a certain amount of assimilation is observed in the form of light coloured selvage bands with a marked flow-structure.

(2) *Medium-grained variety.*

As this variety has been already described by Prof. Holmes, only a few additional observations will be presented here. A series of representative micro-sections taken along the whole outcrop of the Whin Sill was measured by means of Shand's micrometric stage under a 1-inch objective. The results of these measurements brought up to 100 % are presented in Table I. At first sight these results are not comparable with those of Holmes, but in this connexion we must point out that Holmes definitely excluded from his measurement of felspar, not only the decomposition products (sericite, &c.), but also the leucocratic mesostasis, which is included in our case with the felspar, while the melanocratic mesostasis was measured together with the melanocritic constituents (hornblende, biotite, chlorite). The fluctuation in the amounts of minerals in different specimens is to be explained, not so much by the actual variation of the rock, as by the effect of sampling.

Table I.—Mineralogical composition of the medium-grained variety of the Whin Sill (percentages by volume).

	Felspar.	Pyroxene.	Hornblende and chloritic mesostasis.	Iron-ore.	Iron-pyrites.
Crook boring	56·06	35·40	1·51	6·85	0·18
High Force (quarry) ...	57·21	30·70	7·67	4·42	—
High Force (waterfall)	61·00	30·55	2·44	5·77	0·24
Little Whin Sill, Weardale	56·18	33·50	2·25	8·07	—
Greenhead quarry ...	58·30	31·30	3·92	6·48	—
Craig Lough	63·60	30·93	—	5·47	—
Belford...	58·38	27·13	9·20	5·29	—
Little Mill	52·04	26·65	12·80	8·51	—
Average (volume) ...	57·72	30·87	5·05	6·36	
,, (weight) ...	51·28	34·05	4·55	10·12	

There is but little to add to Holmes's description of the constituent minerals. The monoclinic pyroxene was found to be the predominating ferromagnesian constituent, but in some cases (lower part of the sill at Craig Lough) large phenocrysts of the orthorhombic variety were observed. Some of these phenocrysts enclose small felspar laths and also minute crystals of normal monoclinic augite. They also show a marked effect of resorption and are moulded on by the normal pyroxene of the groundmass. This, together with the observed fact that in the fine-grained marginal facies one can sometimes observe microphenocrysts of augite, does not entirely tally with the proposed normal sequence of crystallization (see p. 108). A light-coloured enstatite-augite variety of pyroxene is found sporadically distributed through the Whin Sill. This evidently belongs to an early period of crystallization, and it is greatly autopneumatolized.

(3) *Coarse-grained variety* (*Dolerite-pegmatite*).

Already in 1824, Adam Sedgwick, who had made a thorough survey of the Whin Sill of Teesdale, had noticed the coarse-grained variety, and J. J. H. Teall[1] was the first to give a petrological description of this variety.

[1] J. J. H. Teall, On the chemical and microscopical characters of the Whin Sill. Quart. Journ. Geol. Soc. London, 1884, vol. 40, p. 640.

(*a*) *Field occurrences.*—The coarse-grained variety can be observed in nearly all outcrops of the Whin Sill where the sill attains a considerable thickness in the region of the South Tyne and Tees basins. With the exception of Caw Burn, no coarse whin was ever found north of the Tyne, and it is also absent in the thinner portions of the sill in the outcrops along the Pennine escarpment and in Lune Dale.

The coarse-grained variety is invariably restricted to the upper half of the sill, and occurs in the form of flat bands. The bands are more of the nature of flattened lenticular masses enclosed in the sill, parallel to its intrusive margins, and often show a rapid thinning out accompanied by bifurcation or branching. Very often the bands exhibit a wavy outline, a kind of flow-structure on a large scale being shown by the band as a whole, but not by its constituent minerals among which the fluxion texture is entirely absent. In thickness the bands vary from a fraction of an inch to six feet. The boundary line between the coarse- and the medium-grained rock is always sharp and well defined, but the transition from one variety to the other, as seen in the micro-section, is perfectly continuous.

The coarse-grained variety has been observed in the following localities:

Crook boring, Co. Durham. At Roddymoor colliery, near Crook, a deep boring revealed the presence of the Whin Sill (187 ft. 1 in. in thickness) intruded in the Scar Limestone. Dr. Woolacott,[1] who gave an account of this boring, found the coarse-grained band (4 or 5 ft. in thickness) to occur near the middle of the sill. The rock is remarkably coarse, and some of the pyroxene crystals are over 1 in. in length.

Middleton in Teesdale. Bands of the coarse rock occur in the upper part of the sill, and can be observed in the two quarries south of the river Tees and also near the Whinch Bridge.

High Force, Teesdale. There is a good exposure of several bands in the quarry just above the hotel. Altogether four bands were to be seen in the quarry face in 1927. They were all parallel to the plane of intrusion, thinning out in a westerly direction. Their respective maximum thicknesses were as follows: 2, ½, 6, 6 inches.

Cronkley Fell, Maize Beck, Langdon Beck, and Caldron Snout. At all these localities in Teesdale coarse bands are to be found in the

[1] D. Woolacott, A boring at Roddymoor colliery, near Crook, Co. Durham. Geol. Mag. London, 1923, vol. 60, p. 50.

upper part of the sill. Above the waterfall at Caldron Snout, near the new bridge, there are fresh exposures of a very thick (up to 6 ft.) band which ramifies into a series of undulating veinlets.

Tyne Head, Cumberland. A band 8 in. thick, rapidly thinning out in a westerly direction, is exposed at the foot of the waterfall.

Gilderdale Burn, near Alston, Cumberland. A band 6 to 8 in. in thickness is exposed on the south bank opposite the rapids. This rock is very interesting as it shows pink segregation patches.

Lambley Burn and Black Burn, south-west of Haltwhistle, Northumberland. Coarse bands are found in Lambley and Tindale quarries and also near the waterfall in Black Burn.

Caw Burn, near Haltwhistle, Northumberland. The coarse-grained rock occurs in the form of spheroids, often enclosing fibrous pectolite.

(*b*) *Petrography.*—Megascopically the rock is very coarse and gabbroidal, with conspicuous long blades of lustrous black pyroxene (up to 2 in. in length), often curved and twisted, resembling blades of grass. Frequently the pyroxene blades form clusters radiating inwards into the band. The felspar crystals are in the form of large prisms (but smaller than the pyroxene) and so the rock has a distinct 'black and white' appearance.

Only a very large thin section can give an adequate idea of the texture of the rock. Plate III, fig. 1 shows not only the two varieties but also the nature of the continuous transition of one into the other. A narrow intermediate zone is always present, and it is sometimes of a leucocratic character. In the coarse rock long prisms of pyroxene and felspar can be observed radiating into the band, with the micropegmatite occupying the space between the large crystals.

The texture is hypidiomorpho-granular holocrystalline. Both felspar and pyroxene appear either as hypidiomorphic or idiomorphic crystals, or in graphic intergrowth. Sometimes the same crystal is idiomorphic at one end and allotriomorphic at the other. Green uralitic and ordinary brown hornblende often fringe the pyroxene crystals. Iron-ore occurs in the form of granules and rods (plates). The groundmass is formed by micropegmatite and chlorite (palagonite). In sections rich in micropegmatite, free idiomorphic quartz may be found. Apatite is very abundant, especially in the mesostasis.

A very peculiar feature, observed in nearly all sections of this rock, is what one may call a micro-taxitic texture. The term 'taxitic texture' was introduced by F. Loewinson-Lessing,[1] who defines it as follows:[2] 'Taxitic—alternation of areas of different composition and texture: (*a*) Eutaxitic—banded alternation of different areas, (*b*) Ataxitic—irregular, breccia-like alternation of different areas.'

In our case the irregularly distributed components are the micropegmatite and the pyroxene-felspar-pegmatite. There are patches of these two kinds of pegmatite. In places where the acid micropegmatitic patches (usually coloured red by minute flakes of haematite) reach a large size, the rock assumes a distinctly spotted appearance. But there is a perfect gradation between these true taxitic types to the microtaxitic type.

The coarse-grained rocks from all the localities mentioned above have been sliced and examined under the microscope, while the specimen from the Crook boring has been measured by means of Shand's micrometric stage and also analysed chemically. (Tables II and III.)

The *felspar* occurs mainly in the form of large stout prisms. As a rule it is quite fresh, except in the more acid varieties of the Whin Sill, where turbid felspar is prevalent (sericitized and saussuritized). Quite often it is idiomorphic, especially when surrounded by the micropegmatite. In the last case micropegmatite forms a radiating fringe round the felspar crystals. The felspathic component of the micropegmatitic fringe is always in optical continuity with the outer (albitic) rim of the phenocryst (Plate IV, fig. 3). In contact with pyroxene the felspar is often ragged. It encloses numerous needles of apatite and occasionally magnetite grains (in acid varieties, haematite). Albitic twinning is prominent, often combined with Carlsbad twinning or pericline cross lamination (probably secondary). The progressive continuous zoning, from calcic centre to sodic periphery, is well marked. This absence of rhythmic zoning is shared by the felspars of many igneous rocks which have developed free silica at the last stage of crystallization, as already noted by A. Harker. Although belonging to one generation, the felspar varies in composition within wide limits. The innermost portion corresponds to basic labradorite ($Ab_{35}An_{65}$), while the outer rim may attain the composition of oligoclase or even albite. The mean

[1] F. Loewinson-Lessing, Note sur les taxites et sur les roches clastiques volcaniques. Bull. Soc. Belge Géol., 1891, vol. 5, p. 103.

[2] F. Loewinson-Lessing and D. Beliankin, Petrographic Tables. (In Russian) 2nd edition, 1927, p. 76.

specific gravity (2·646) and the mean refractive index (from 1·545 to 1·560) seem to indicate that the felspar in its average composition corresponds to medium or basic andesine, and on the whole it appears to be slightly less calcic than the felspar from the medium-grained variety.

Table II.—Mineralogical composition of the coarse-grained variety of the Whin Sill (percentages by volume).

	Crook boring.	High Force.	Average Volume.	Average Weight.
Felspar	41·35	41·18	41·27	37·21
Micropegmatite	17·71	18·23	17·97	15·86
Quartz	2·80	2·76	2·78	2·47
Pyroxene	20·25	19·35	19·80	22·22
Hornblende, chlorite, &c. ...	10·54	9·72	10·13	9·20
Iron-ore	7·19	8·68	7·93	12·82
Iron-pyrites	0·16	0·08	0·12	0·22

Table III.—Chemical composition of the Whin Sill.

	I.	II.	III.
SiO_2	49·70	50·12	50·51
TiO_2	2·70	2·72	2·33
Al_2O_3	15·64	15·78	14·61
Fe_2O_3	2·42	2·44	3·50
FeO	11·35	11·46	8·85
CaO	8·03	8·10	8·76
MgO	3·06	3·09	5·32
MnO	0·14	0·14	0·22
Na_2O	2·90	2·92	2·55
K_2O	1·22	1·23	1·19
P_2O_5	0·55	0·55	0·31
FeS_2	0·24	0·24	0·50
CO_2	trace	—	—
H_2O (+110° C.) ...	1·20	1·21	1·35
H_2O (−110° C.) ...	0·70	—	—
	99·85	100·00	100·00

I. Coarse-grained variety of the Whin Sill. Crook boring, Co. Durham. Analysis by W. H. Herdsman.

II. Same, recalculated to 100 % (minus hygroscopic water).

III. Average of five analyses of the medium-grained variety of the Whin Sill: Caldron Snout (Teall), Borcovicus (Teall), Rotherhope (Finlayson), Snook Point (Smythe), Scordale Beck (Harwood).

Pyroxene. The predominant dark-brown pyroxene occurs in the form of long prismatic crystals, often curved and twisted. Although one may occasionally see broken pyroxene crystals with cracks sealed up by iron-ore, the curvature and twisting cannot be attributed to purely mechanical causes posterior to their formation.

In longitudinal sections perpendicular to the twinning plane (100) the basal parting appears in the form of fine striations, producing the typical 'herring-bone' structure (fig. 1). From the examination of several micro-sections the general impression is gained that this lamination is of a secondary origin. When highly developed it is often accompanied by a beautiful 'hour-glass' structure (plate IV, fig. 4), and also by a certain degree of alteration along the planes of lamination

FIG. 1. Pyroxene crystal (8 mm. long) with 'herring-bone' structure in the coarse Whin Sill, Crook boring, Co. Durham. Iron-ore, black; felspar, unshaded; hornblende, dark striation.

It may be that the two phenomena—lamination and 'hour-glass' structure—are closely connected, depending, as already suggested by Teall in reference to the lamination, on the water present in the mineral. Besides the alteration along the basal planes, the pyroxene crystals are often fringed by hornblende (green uralitic and normal brown variety).

Another interesting feature of the pyroxene is the frequent occurrence of the so-called 'polysomatic' structure, as defined by A. C. Lawson.[1] The 'polysomatic' crystals appear to be formed by a mosaic of areas having different optical orientation, while preserving their physical continuity, as defined by cleavage, &c.

The analyses of pyroxenes isolated from the coarse-grained variety of the Whin Sill by J. J. H. Teall show the presence of about 30 % of magnesium metasilicate molecule, but as the optical axial angle of this pyroxene is apparently normal, it cannot be called enstatite-

[1] A. C. Lawson, On the geology of the Rainy Lake region. Ann. Rep. Geol. Survey Canada, 1887, vol. 3.

augite. Typical 'enstatite-augite' in the form of almost colourless, greatly decomposed prismatic crystals with a well-marked 'herring-bone' structure is found sporadically in the coarse rock; and, as in the medium-grained rock, it is an early product of crystallization. One may suppose that the 'enstatite-augite' and the normal brown augite belong to the same genetic series. If so, we may represent the ferro-calc-magnesian reaction series as follows:

Olivine
↓ Discontinuity (resorbed)
Enstatite-Hypersthene
↓ Discontinuity (partly resorbed)
Clinoenstatite-Clinohypersthene
↓ } Enstatite-Augite series (continuous).
Diopside-Hedenbergite

This scheme apparently agrees with the interpretation of the process as proposed by A. Holmes, but it certainly fails to explain the early crystallization of augite as observed in certain sections of the fine- and medium-grained varieties. It may be that the scheme proposed is far too simple and that we have a separate branch of the augite series, along which crystallization began at an early stage and joining the enstatite-hypersthene branch lower down.

Pyroxene-felspar graphic intergrowth can be observed in nearly all specimens of the coarse-grained rock (plate IV, fig. 5). In places it can be even observed with the unaided eye. It occurs in definite taxitic patches alternating with patches of micropegmatite. The pyroxene of the intergrowth is either continuous with the large prismatic crystals (fig. 1) or is quite independent of them. The felspar of the intergrowth is definitely in optical continuity with the large crystals. Polysomatic structure is frequently observed in the pyroxene. Sometimes the intergrowth simulates the form of fucoid algae, similar to the so-called 'cervicorn' type of intergrowths described by H. H. Thomas[1] (fig. 6).

The pyroxene-felspar intergrowth, although of rare occurrence in igneous rocks, has been described by many authors. As a rule it is confined to the coarse-grained varieties of quartz-dolerites or similar rocks. But the question of its origin and its relation to the 'gabbroidal eutectic' has never been adequately discussed.

Micropegmatite is very abundant in the mesostasis, between the large crystals of pyroxene and felspar. Usually it forms a radiating

[1] H. H. Thomas, Geol. Survey Memoir on Mull, 1924, p. 333.

fringe round felspar crystals. The transverse section of this fringe gives a characteristic appearance of triangular and hexagonal areas of quartz.

Quartz occurs as large patches in places rich in micropegmatite, and usually it is in optical continuity with the quartz of the micropegmatite. It is, as a rule, allotriomorphic, but in acid varieties of the coarse Whin Sill it occurs in the form of fine idiomorphic crystals surrounded by palagonite.

Hornblende, biotite, and *chlorite* are found in the mesostasis. Biotite is sometimes seen replacing hornblende, and it was probably formed during the final stage of consolidation together with chlorite. The last mineral occurs in cloudy greenish masses associated with micropegmatite and also in the form of finely crystalline spheroido-fibrous aggregates (palagonite). In places chlorite replaces felspar in the micropegmatite (fig. 8).

Apatite, in the form of very long slender needles, is very abundant, especially in the groundmass.

Iron-ore occurs in the form of large grains, granular clusters, and long narrow plates, frequently with a parallel arrangement. The majority of these plates are of early formation, but in certain places iron-ore is seen to cement broken crystals of pyroxene and fill cracks in pyroxene and felspar. We may therefore assume that the range of crystallization of the iron-ore was extensive. The presence of white bands of leucoxene and the data of the analysis show that we have here a titaniferous magnetite.

Iron-pyrites is found in small quantity, either as minute spongy spheroids or as infillings of minute cracks.

III. Certain Exceptional Varieties of the Whin Sill.

(1) *Red acid segregations.*

As has already been pointed out, even the normal coarse-grained rock has a tendency towards the development of a taxitic texture. Under certain favourable conditions this tendency resulted in the formation of a macro-taxitic rock with visible red spots. The attention of the author to this interesting variety has been drawn by Dr. J. A. Smythe, who is intending shortly to publish a special paper dealing with it. A fine example of this rock may be found in Gilderdale, near Alston. Under the microscope, this rock appears like the ordinary coarse Whin Sill, except for the fact that both felspar and pyroxene are greatly decomposed (saussuritized and chloritized) and there is an abundance of a granophyric groundmass segregated in definite areas. A large amount of greenish material, together with hornblende and mica, is also present in the groundmass. Free quartz is abundant, and often it presents idiomorphic outlines against the chloritic mesostasis. This mesostasis is composed of a fibrous brownish-green chlorite. In its chemical composition (Table IV, analysis I) it differs greatly from the normal dolerite, being richer in silica, which is entirely due to the abundance of granophyric patches.

Table IV.

	I.	II.	III.
SiO_2	54·85	58·10	65·20
TiO_2	2·07	1·65	0·39
Al_2O_3	12·92	14·49	13·72
Fe_2O_3	0·88	—	3·63
FeO	12·51	9·51	3·72
CaO	7·87	5·05	2·79
MgO	2·62	3·32	1·01
MnO	0·08	0·16	—
Na_2O	2·57	2·76	5·22
K_2O	1·35	2·36	2·17
P_2O_5	0·57	0·73	0·38
FeS_2	0·11	—	—
CO_2	trace		—
H_2O (+110° C.) ...	1·63	1·61	1·27
H_2O (−110° C.) ...	0·21		0·72
	100·24 %	99·74	100·22
Sp. gr.	2·845	2·725	2·652

I. Whin Sill. Coarse-grained with red spots. Gilderdale, near Alston, Cumberland. Analysis by S. I. Tomkeieff. A partial analysis of another sample of the same rock gave SiO_2 56·85 and H_2O (+110° C.) 2·89 %.

II. Aplitic inclusions from the Whin Sill. Snook Point, Northumberland. Analysis by J. A. Smythe.

III. Felsite. Red veinlet in the Whin Sill. Alnwick Moor, Northumberland. Analysis by S. I. Tomkeieff.

Red acid veinlets are also found in many places in the Whin Sill. They are composed of a fine-grained felsitic rock almost entirely consisting of turbid acid felspar and micropegmatite. The red colour is apparently due to the presence of innumerable minute flakes of haematite. Unlike the red patches in the coarse rock, the red veinlets show a definite intrusive relation to the normal dolerite which they invade, but there is no distinct marginal chilling to be observed. In one place (Tindale quarry) a red veinlet was seen to originate in a band of a coarse-grained slightly taxitic rock and continue into the surrounding medium-grained dolerite. Apparently the red veinlets represent a pure acid differentiate of the quartz-dolerite magma, subsequently injected into the solidified, but still hot rock (absence of marginal chilling). This differentiation took place in the coarse rock, and we can trace the successive stages of this differentiation from the micro-taxitic rock and through the macro-taxitic rock to the final squeezing out of the felsitic fraction and red-vein formation.

The chemical analysis of the red rock is given in Table IV, analysis III. It is a fairly acid rock almost corresponding to a granitic magma in composition. In comparison with the normal rock it is very rich in alkalis, and it is significant that the amount of Fe_2O_3 is actually greater than in the normal rock, which agrees well with the fact that the magnetic iron-ore is present in a very small amount and haematite has developed in its place.

(2) *Spheroidal aplitic inclusions.*

These inclusions have been described by J. A. Smythe [1] as occurring at Snook Point. They vary in size from $\frac{1}{8}$ to $\frac{7}{8}$ in. in diameter, and have a curious development of plates of iron sulphide (pyrrhotine) in their lower hemisphere, which produces a faceted appearance. The analyses of these inclusions as made by Smythe is given in Table IV (analysis II), and one can see that it is a fairly acid rock, having in composition an affinity to a syenitic magma (but somewhat poorer in alkalis). It occupies an intermediate position between the taxitic Whin Sill and the red veinlets.

Dr. Smythe was kind enough to place at the author's disposal a large number of micro-sections of these inclusions. They all show a sharp but continuous transition into the normal dolerite. All of them have large plates of pyrrhotine (and titanomagnetite) in the lower hemisphere. The rock of the inclusions is much finer in grain than the normal dolerite, and is characterized by the predominance of an acid felspar (rather turbid) and an almost complete absence of pyroxene, the place of which is taken by chlorite and hornblende. The rock could be called a doleritic aplite.

One section proved to be of particular interest (plate III, fig. 2). The nucleus is a pure aplitic rock largely composed of a turbid acid

[1] J. A. Smythe, Inclusions in the Great Whin Sill of Northumberland. Geol. Mag., 1914, dec. 6, vol. 1, pp. 244–255.

felspar (oligoclase or albite) with a scanty mesostasis of micropegmatite and chlorite and abundant apatite. It is surrounded by large plates of pyrrhotine with some titanomagnetite. Beyond the bordering plates lies the outer zone of the inclusion, which both in texture and composition is intermediate between the nucleus and the normal dolerite. Really we have here an inclusion within an inclusion. The transition of the outer zone into the surrounding normal dolerite is sharp but continuous, and marked by tangentially placed felspars.

There can be hardly any doubt that the inclusions are a product of differentiation of the quartz-dolerite magma. Dr. Smythe makes the suggestion that they may represent a remolten product of an early stage of crystallization. This is hardly possible, for an early product of crystallization would be at least as acid as the magma itself, if not more basic. Instead of this we may suggest that the inclusions are solidified globules of a fraction of the magma rich in volatiles and sulphur. This means that we have here a liquation-differentiation with a separation of one fraction in the form of liquid globules. Under the particular condition of chemical equilibrium in this fraction, iron separated in the form of large plates of pyrrhotine which sank to the bottom of the globule, leaving a portion richer in silica, which being more viscous formed a finer-grained aplite.

(3) *Pectolite inclusions.*

At Caw Burn, near Haltwhistle, the coarse-grained segregations occur in the form of spheroids up to 10 cm. in diameter. As a rule each of these segregations encloses at the top an eccentrically situated cavity infilled with a radial aggregate of pectolite. Pectolite also occurs independently of these spheroids in the vesicles in the normal dolerite and in veinlets. The coarse rock varies from a normal gabbroid variety with large pyroxene crystals exhibiting a fine schiller lustre, to a light-greenish leucocratic rock very rich in pectolite in its groundmass. Microscopically, the dark variety of the coarse rock is similar to that found elsewhere, with a pyroxene showing a perfect 'hour-glass' structure (fig. 4) and a well-developed basal lamination. The felspar is greatly sericitized and saussuritized. In the leucocratic variety the pyroxene is less abundant and mostly found in graphic intergrowth with felspar. There is also more acid felspar present and very little micropegmatite in the groundmass, the place of which is taken by a fibrous pectolite, which can also be seen to encroach on felspar. Small laths of green hornblende are often found embedded in pectolite. It is highly pleochroic and has a small extinction-angle, and is perhaps arfvedsonite. In places, the hornblende laths are embedded in a finely-radiating non-pleochroic palagonite. Pectolite from this locality has been analysed by J. A. Smythe.[1]

What is the origin of pectolite in the Whin Sill? That hydrous silicates are formed during the last period of consolidation of an igneous rock is a well-known fact and need not be discussed here, but how are we to explain the presence in the vesicles of many minerals rich in calcium? In the normal course of crystallization of the basaltic magma the calcium-rich minerals crystallize out first so as to leave a more alkaline residue. It may be that calcium is retained by the hydro-gaseous phase of the magma, or that the calcium-rich hydrous silicates are produced through the reaction between the previously-formed calcium silicates and water-vapour, or, finally, that they are formed through assimilation of limestone by the magma. The data of our observations is insufficient to solve this problem.

IV. The Specific Gravity.

A new set of specific gravity determinations of the different varieties of the Whin Sill was obtained by the author by means of a hydrostatic balance and corrected to 4° C. The rocks are grouped according to the classification outlined above, i. e. into: (1) Fine-grained (contact facies); (2) Medium-grained (dolerite); (3) Coarse-grained (gabbro).

Locality.	1.	2.	3.
Crook boring	—	3·015	2·863
,, ,, ...	—	3·010	2·871
,, ,, ...	—	3·033	2·932
,, ,, ...	—	3·010	2·948
,, ,, ...	—	3·013	2·951
Middleton in Teesdale	2·938	2·958	2·941
Blea Beck (Teesdale)	2·896	—	—
High Force (quarry)	—	2·983	2·960
,, ,, (waterfall)	2·884	2·927	—
Langdale Beck	—	2·952	2·948
Maize Beck	—	2·947	2·923
Caldron Snout	—	2·941	2·920
,, ,, ...	—	2·976	3·020

[1] J. A. Smythe, Minerals of the north country: silicates. The Vasculum, Newcastle-upon-Tyne, 1924, vol. 10, p. 100. [Min. Abstr., vol. 3, p. 25.]

Locality.	1.	2.	3.
Tyne Head...	—	2·944	2·978
,, ,, ...	—	—	3·104
Hargill Beck	—	2·908	—
Lune Moor...	—	2·945	—
Gilderdale, normal	2·942	2·952	3·004
,, ,, ...	2·960	—	2·990
,, few pink spots ...	—	—	2·935
,, rich in pink spots ...	—	—	2·845
,, ,, ,, ...	—	—	2·831
Black Burn	2·933	3·039	2·958
Copt Hill	3·028	3·002	—
Stanhope (Little Whin Sill) ...	—	2·996	—
Caw Burn	—	2·996	2·976
Craig Lough	—	2·943	—
Borcovicus...	2·880	2·965	—
Average	2·933	2·975	2·944

We see that on the average the coarse-grained variety is lighter than the medium-grained variety.

V. On the Genesis of the Coarse-grained Variety of the Whin Sill and Acid Segregations, and its Bearing on the Question of Magmatic Differentiation.

The quartz-dolerites are widely spread in space and time. They always occur in the form of sills and dikes, and usually present the same petrographical characters as the Whin Sill. Almost everywhere these rocks exhibit bands or patches of coarse gabbroidal rock, as a rule sharply separated from the normal dolerite. The coarse rock from many various localities shows the same marked development of micropegmatite with a tendency to patchy segregation, as in the Whin Sill. Sometimes a pyroxene-felspar intergrowth is also to be found, and also acid veinlets within the body of the normal dolerite. This world-wide similarity of quartz-dolerites and their varieties is most striking. They have been recorded and described, besides in England and Scotland, in Sweden, Russia, France, India, Congo, South Africa, British Guiana, U.S.A., Canada, Australia, Antarctica, &c. It would be impossible to give here all the numerous references, but it is amazing how the description of certain quartz-dolerites from New England (Trias), British Guiana (Cretaceous), and Canada (pre-Cambrian) could be matched by those of the Whin Sill.

Chemically, all these rocks belong to one definite magmatic type, which is, as a matter of fact, nothing else than the 'plateau basalt' magma type (excluding the extreme olivine-basalt sub-type), as the analyses compiled by H. S. Washington show.[1] We may assume, therefore, that the quartz-dolerite magma is the hypabasal representative of the primary 'plateau-basalt' magma.

Our study of the Whin Sill, and especially its products of differentiation, may therefore throw some light on a wider problem of petrogenesis. First we shall discuss the genesis of the coarse bands.

As the comparison of the chemical analyses shows (Table III), the coarse rock does not differ much in its chemical composition from the normal dolerite. There are some minor differences, such as the content of FeO and MgO being respectively higher and lower than in the normal rock, but contrary to all expectation the silica percentage is even slightly lower in the coarse rock, although this small difference in silica content has no real significance. The essential difference of the two varieties apart from the texture lies in the mineral composition. The following table shows this quite clearly :

	Medium-grained variety.		Coarse-grained variety.	
Felspar	51·28	51·28 %	37·21	55·54 %
Micropegmatite ...	—		15·86	
Quartz	—		2·47	
Pyroxene	34·05	38·60	22·22	31·42
Hornblende, &c. ...	4·55		9·20	
Iron-ore	10·12		13·04	

In the coarse rock the leucocratic portion is more abundant, and this is mainly due to the development of quartz. An early withdrawal of iron from the magma in the form of iron oxide and also in a larger quantity (there is more of the iron-ore in the coarse rock) is probably one of the causes for the appearance of free silica in the coarse rock. This silica in the normal course of crystallization would probably form an iron metasilicate as part of the pyroxene molecule. This is why we also see a corresponding decrease in the amount of melanocratic silicates in the coarse rock. The amount of pyroxene is still further reduced by the higher development of hornblende, mica, and chlorite. In this way we see that the different mineral composition of these two rocks can be balanced against their identical chemical composition, and so we may apply to them the term 'heteromorphic' as proposed by Lacroix.

[1] H. S. Washington, Deccan traps and other plateau basalts. Bull. Geol. Soc. Amer., 1922, vol. 33, p. 765.

There may be many hypotheses advanced to explain the origin of heteromorphic rocks, but we can at the outset dismiss some of them. First we may dismiss the hypothesis which would explain the genesis of the coarse bands by the squeezing out of the residual liquor (filter pressing). Besides a total absence of textural evidence in favour of this hypothesis, the chemical identity of the two rocks speaks against it. The same applies to the hypothesis of a latter injection, which was once applied to explain the origin of banded gabbro of Skye, but was rejected by Geikie and Teall,[1] who sought the cause of banding in the heterogenity of magma prior to injection. After having excluded the above hypotheses, let us consider the probable causes which led to the formation of the coarse dolerite-pegmatite. Generally speaking the grain-size in an igneous rock depends on three principal factors, viz. (1) chemical composition of the magma, (2) rate of cooling, and (3) viscosity of the magma. As a matter of fact, the last of the three factors is closely bound up with the first.

In our case the chemical composition and the rate of cooling must have been the same for both varieties. We have therefore to suppose that the coarse rock was crystallized out of a magma of lower viscosity. It is a well-known fact that the presence of even a small amount of volatiles greatly lowers the viscosity of the magma. Besides the evidence derived from the consideration of texture, the abundance in the coarse rock of hydrous minerals, such as chlorite, mica, hornblende, as well as micropegmatite, speaks in favour of this view. E. V. Shannon, who has described a dolerite-pegmatite from a sill at Goose Creek, Virginia, a rock remarkably similar to the coarse variety of the Whin Sill, thinks that 'it owes its peculiar feature to concentration of volatile constituents, notably water, into spots of greater or less size which remained fluid after the main mass of the diabase solidified and permitted the growth of large crystals producing unusually coarse texture'.[2] In his valuable paper he also discusses numerous other occurrences of dolerite-pegmatite described in American literature.

The only way to explain the formation of patches of magma rich

[1] A. Geikie and J. J. H. Teall, On the banded structure of some Tertiary gabbros in the Isle of Skye. Quart. Journ. Geol. Soc. London, 1894, vol. 50, p. 645.

[2] E. V. Shannon, The mineralogy and petrology of intrusive Triassic diabase at Goose Creek, Loudoun County, Virginia. Proc. U.S. Nat. Mus., 1924, vol. 66, art. 2, pp. 17–18.

in volatiles (including water) is by postulating a sort of liquation-differentiation within the body of the magma prior to its injection into the strata. Possibly this 'wet' differentiation formed in the intercrustal basin was caught up by the ascending magma and stretched out in the form of lozenge-shaped tabular bodies parallel to the walls of the injection chamber. These 'wet' portions were affected by cooling in the same way as the surrounding normal magma, but being more fluid they crystallized more freely, with the formation of long crystals of pyroxene and felspar. The combined effect of the volatiles and the rate of crystallization resulted also in a different physico-chemical equilibrium leading to a formation of a heteromorphic rock.

Certainly there is nothing new in the liquation-differentiation hypothesis, which is supported by such authorities as F. Loewinson-Lessing and R. A. Daly, although at the present time it finds many opponents among petrologists. Geikie and Teall evidently had this idea in mind when they wrote, that 'we therefore conclude that the cause which produced the banding must have operated before the crystallization of the minerals from the igneous magma'.[1] Harker[2] also thinks that the banded gabbros of Skye have originated through the injection of a heterogeneous magma, and Loewinson-Lessing uses the term 'macro-emulsional' magma in explaining the origin of banded gabbros in the Ural Mountains.[3]

It would be as well to explain here that in postulating a liquation of magma we do not imply a perfect immiscibility of the fractions, such as that of the sulphide fraction in a molten slag. The immiscibility of the fractions must be regarded more as a type of limited miscibility, conditioned by the factors of temperature, pressure, and time. The volatiles might concentrate in a certain part of the magma reservoir and form a 'wet' fraction which, although not absolutely immiscible with the rest of the magma, when caught up by the normal magma during injection would remain separated from it, simply because the crystallization would take place before such mixing could be accomplished. This relative immiscibility, therefore, is only conditioned by the time factor. An analogy is given by a mixture of porridge and milk, which on stirring at first forms

[1] A. Geikie and J. J. H. Teall, loc. cit., 1894, p. 653.

[2] A. Harker, The Tertiary igneous rocks of Skye. Mem. Geol. Survey, 1904.

[3] F. Loewinson-Lessing, Geological description of the Youjno-Saoserskaya dacha and Denishkin kamen. Trav. Soc. Nat. St.-Pétersbourg, 1900, vol. 30, livr. 5.

stringers of a milk-rich portion in a thick portion, and only after a certain time becomes perfectly homogeneous.

As seen from its finished product—the coarse dolerite-pegmatite—the 'wet' fraction is characterized by its own sequence of crystallization. Apparently under 'wet' conditions there is less affinity between the iron oxides and silica, and this results in an increased formation of iron-ore and liberation of free silica, which at the last stage of crystallization formed a micropegmatitic intergrowth with the alkali felspar. Theoretically, in the 'wet' portion a more perfect equilibrium must be attainable than in the 'dry' portion, due to the absence of super-saturation, under-cooling, &c. This is probably why we observe here several eutectics (or eutectoids), such as the intergrowths of quartz-orthoclase-albite, pyroxene-felspar, orthorhombic and monoclinic pyroxenes, and magnetite-ilmenite.

The peculiar course of crystallization in the 'wet' fraction also explains the origin of red patches and acid veins. Whereas in the normal doleritic magma hardly any acid residual liquor is formed at the last stage of crystallization, in the 'wet' fraction we observe a marked movement of the liquidus towards the acid pole. The taxitic texture so prevalent in the coarse rock is due to the tendency of the acid liquidus to segregate in definite spots. Under favourable conditions the acid liquor can even be squeezed out into cracks in the surrounding rock, with the resulting formation of aplitic and felsitic veinlets. Apparently under certain conditions the separation of the acid portion can take place while the magma is still liquid (magmatic emulsion), so that the blobs of the acid differentiate on cooling form the spherical inclusions described by Dr. Smythe.

In this way we can follow in the coarse Whin Sill all the stages of differentiation from the formation of a micro-taxitic rock through a typical taxite (spotted rock) to the separation of granophyric portion in the form of red veinlets. The degree of separation depends, not only on the viscosity of the magma, but also on the time during which it cooled. In large intercrustal magmatic reservoirs, therefore, we may expect a greater and more complete differentiation of the quartz-dolerite magma with the resulting formation of olivine-gabbro and granophyre. This large-scale differentiation certainly cannot be attained by filter-pressing alone; it may be the combined effect of liquation- and crystallization-differentiations, and only in certain favourable circumstances accentuated by the filter-pressing. It would be impossible with certainty to apply directly the process of differentiation as observed in the Whin Sill to this great petrogenetic problem, but one must not forget that similar causes are in operation whether we are considering small or large phenomena in nature.

In conclusion I would like to thank Prof. A. Holmes for his kind help and friendly discussion of the problems involved in this paper, without making him responsible for any of the views expressed in it; Dr. J. A. Smythe for the loan of micro-sections of the inclusions and the specimen of the taxitic rock from Gilderdale; and also to all my colleagues of the Geological Department of Armstrong College for their friendly advice and co-operation.

EXPLANATION OF PLATES III AND IV.

FIG. 1. Whin Sill, coarse-grained variety passing into the medium-grained variety. Crook boring, Co. Durham.

The upper portion shows the coarse rock (*a*) with large crystals of felspar and pyroxene radiating into the band, and the micropegmatitic mesostasis filling up the lacunae. A narrow transition zone (*b*) separates this rock from the normal medium-grained dolerite (*c*) with sub-ophitic augite and small felspar laths. Ordinary light. ×20.

FIG. 2. Inclusion in the Whin Sill. Snook Point, Northumberland.

(*a*) Acid nucleus composed of a meshwork of turbid acid felspar, micropegmatite, some hornblende and apatite. It is surrounded by large plates of pyrrhotine. (*b*) Outer zone of the inclusion, of a slightly coarser texture than the nucleus, in which the ferromagnesian minerals (mainly chlorite) are more developed. (*c*) Normal medium-grained dolerite surrounding the inclusion. Ordinary light. ×15.

FIG. 3. Whin Sill, coarse-grained. Crook boring, Co. Durham.

Felspar phenocrysts with a continuous zonal structure in a groundmass of micropegmatite. The outer acid zone of the phenocrysts is continuous with the felspar of the micropegmatite and has straight extinction. The extinction-angle of the inner portion is 18°. Nicols crossed. ×25.

FIG. 4. Whin Sill, coarse-grained. Caw Burn, Northumberland.

'Hour-glass' structure of pyroxene. Section approximately perpendicular to the *c*-axis, so that the basal lamination is not shown. Ordinary light. ×22.

FIG. 5. Whin Sill, coarse-grained. Crook boring, Co. Durham.

Pyroxene-felspar intergrowth. Ordinary light. ×25.

FIG. 6. Whin Sill, coarse-grained. Gilderdale, Cumberland.

Pyroxene-felspar intergrowth, 'cervicorn' type. Ordinary light. ×30.

FIG. 7. Whin Sill, coarse-grained. Gilderdale, Cumberland.

Semi-idiomorphic crystal of quartz embedded in a finely fibrous palagonite. A plate of titaniferous iron-ore traverses the section. The remainder is made up of decomposed felspar, pyroxene, and micropegmatite. Ordinary light. ×22.

FIG. 8. Whin Sill, coarse-grained. Gilderdale, Cumberland.

Palagonite replacing felspar in the micropegmatite. Ordinary light. ×25.

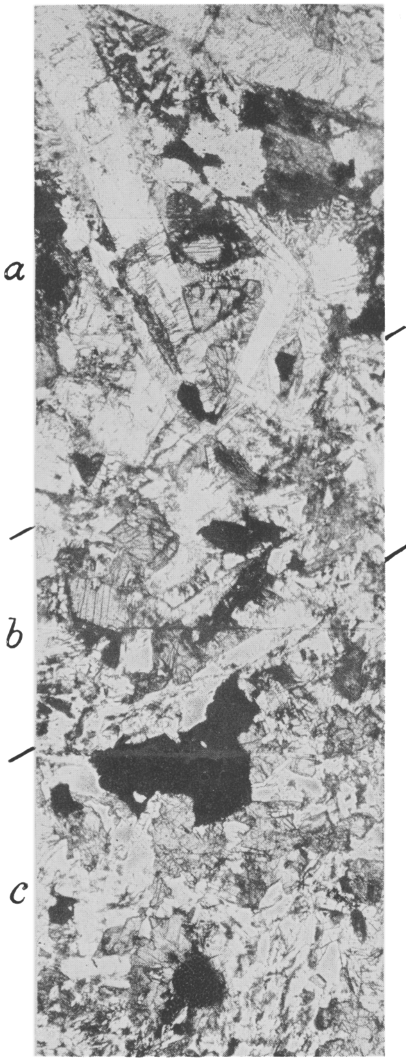

Fig. 1

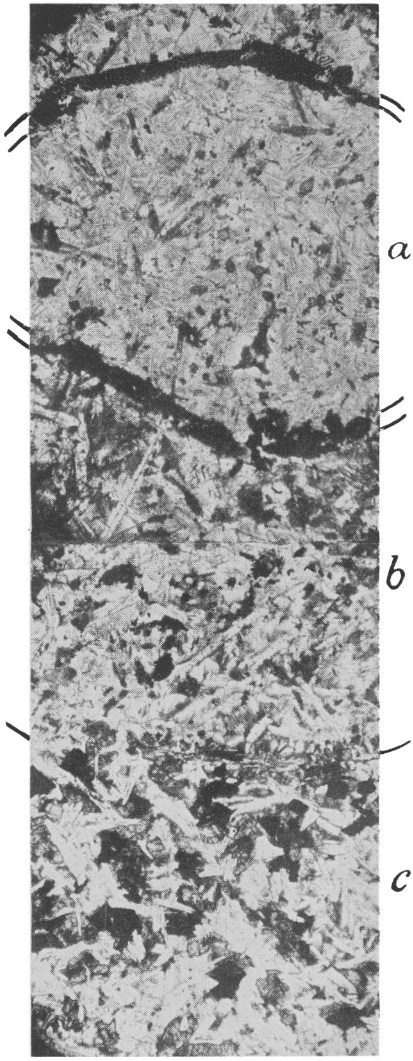

Fig. 2

S. I. Tomkeieff: The Whin Sill

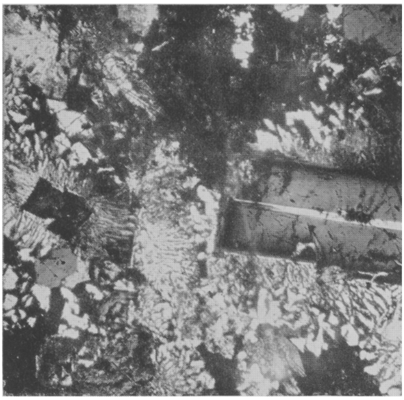

FIG. 3

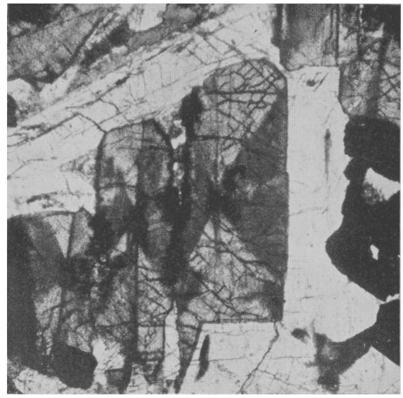

FIG 4

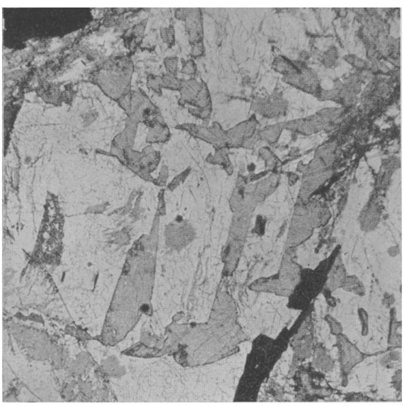

FIG. 5

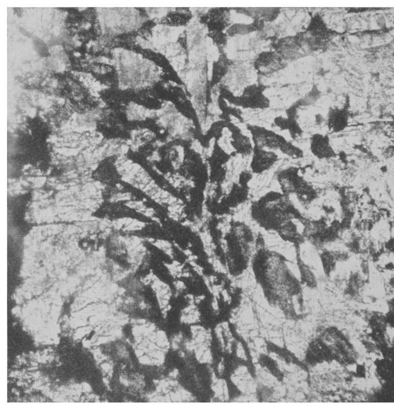

FIG. 6

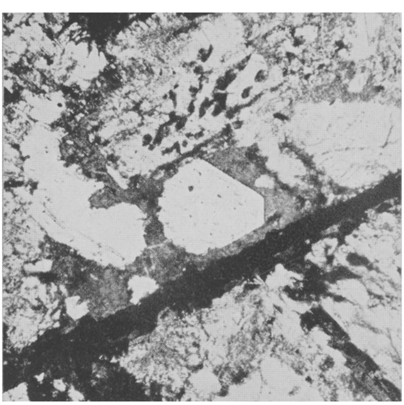

FIG. 7

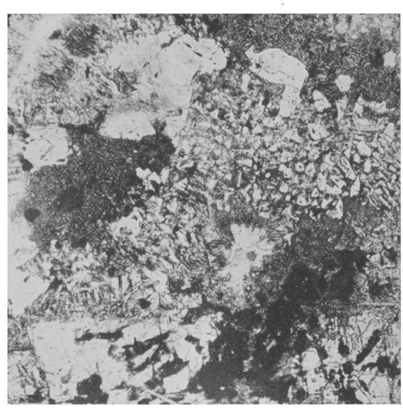

FIG. 8

S. I. TOMKEIEFF: THE WHIN SILL