PETROGRAPHY OF THE NICKELIFEROUS NORITE OF ST. STEPHEN, NEW BRUNSWICK

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ABSTRACT

The St. Stephen complex comprises harzburgite, olivine-norites (including banded troctolitic and anorthositic types) and olivine-hypersthene gabbro, of presumed Devonian age. It is intruded into quartz-chlorite-mica phyllites of the Charlotte Group, which show little contact metamorphism. In contact with the phyllites, the complex has a marginal zone of quartz-hornblende-gabbro. The norites enclose xenoliths of free-silica hornfels (including biotite, cordierite and hypersthene types), silica-poor hornfels (plagioclase-spinel) and pyroxene-granulite. Except in the marginal zone and near xenoliths, hydroxyl-bearing minerals are relatively scarce. Pegmatitic segregations in the norite carry concentrations of ilmenite and show a higher soda/lime ratio than the norites, but no increase in potash, which is low throughout the complex. Lenticular bodies with magnetite, pyrrhotite, pentlandite and chalcopyrite were formed by metasomatism of the norite, associated with development of hydroxyl-bearing minerals which were, however, themselves destroyed where the sulphide mineralization is most intense. A post-sulphide biotite-spessartite dike is recorded, and the development of anthophyllite and chrysotile along post-sulphide fractures is noted.

INTRODUCTION

The border town of St. Stephen, in Charlotte County, New Brunswick, is situated on the St. Croix river, 80 miles S.S.W. of Fredericton, opposite the town of Calais, Maine. At St. Stephen and in the district north and west of the town, a complex of basic intrusives covering some nine square miles is exposed, containing concentrations of pentlandite-bearing pyrrhotite. During 1932–35, while I was working in Professor Larsen's laboratory at Harvard as a Commonwealth Fund Fellow, I paid several visits to St. Stephen to carry out the field work which forms the basis of the present study.

It is a pleasure to be able to pay tribute here to the inspiration and guidance Professor Larsen has given to several generations of petrographers, and to mention the esteem in which his work is held, far beyond the confines of his own country.

The laboratory work has been continued in England. It had been hoped that circumstances would make it possible to resume and amplify the field work. As, however, the war and postwar situations have made it unlikely that this hope will be fulfilled, it has seemed best to record the results so far obtained.

The cost of the chemical analyses has been defrayed by a grant made in 1939 by the Government Grants Committee of the Royal Society. I also wish to acknowledge my gratitude to Professor L. C. Graton for opportunities to examine polished sections made by his method at

Harvard, and to Dr. J. Phemister for laboratory facilities at the Geological Museum, London, during the earlier stages of the work; I also wish to record my thanks to Mr. and Mrs. O. W. Dunham of St. Stephen, my hosts in the field.

History of Research

The first description of the area is due to L. W. Bailey and G. F. Matthews (1872, p. 32), who remark:

> "Just north of the town of St. Stephen, and occupying a position between the syenitic gneisses . . . and the mica schists which appear to overlie them, are limited outcrops of dioritic rock which differ in many respects from any strata that we have met elsewhere. They are of very dark, almost black colour, with a very evident and regular stratification, often including layers of dark green serpentine, while in the mass of the rock, besides white feldspar and hornblende—the latter predominating—crystalline masses of diallage are occasionally met with. These rocks, which have been examined *in situ* by Dr. (T. Sterry) Hunt, and by whom the serpentines have been found to yield both chrome and nickel, are apparently connected with the underlying syenitic gneiss rather than the schistose rocks which succeed them to the northward."

H. P. H. Brummell (1892, p. 112) records prospecting operations for nickel and copper in "coarse-grained diorite" on the Todd, Ganong and Carroll properties. These prospects are again mentioned by R. W. Ells (1903, p. 156) who states that pockety masses of nickel-bearing sulphides occur in gabbros which have penetrated black and grey slates of doubtful age, the slates being metamorphosed locally to chiastolite- and mica-schists. C. W. Dickson (1906, p. 236), who made a petrographical study of material from the Ganong property, showed that the sulphides corrode and replace, along lines of brecciation, an intrusive rock which he regards as transitional between gabbro and diabase. He considered that the sulphides were "prominently associated with hornblende and chlorite," and were therefore not direct magmatic segregations. In a paper among the first to record the application of metallographic technique to the investigation of natural opaque minerals, W. Campbell and C. W. Knight (1907) described the relations of the sulphides in the ores of Sudbury and also those of St. Stephen. In 1929–30 New York interests prospected an area north of the town, according to an account by B. Low (1930) in which results of geophysical investigation, diamond drilling and metallurgical tests are given. In 1946 a preliminary geological map, by G. S. Mackenzie and F. J. Alcock, with descriptive notes, was published by the Geological Survey of Canada.

Field Relations

The St. Stephen complex forms a small part of a plutonic body of batholithic dimensions which is mapped along the Atlantic coast of

Maine from Frenchman Bay to Englishman Bay, and which then turns inland through Whitneyville and Grove to Calais (Keith, 1933). In New Brunswick it continues E.N.E., passing north of St. George and extending beyond Bayard and Blaydon. The total length is about 140 miles and the average width about 12 miles. The St. Stephen area is an embayment on the north-west side of this pluton, separated from the main mass on the Canadian side by a tongue of Palaeozoic rocks between St. Stephen and Oak Bay, but linking southwards with the main mass in the United States. The rocks of the pluton are classified as 'St. George Intrusives' by MacKenzie and Alcock (1946) on the Canadian side; they include, in the neighborhood of St. George, pink microcline-bearing granite, and dark gray quartz-augite-diorite which have been quarried for building stone.

The norite-complex occupies the ridges and valleys for a distance of some 2½ miles north and west of the town of St. Stephen. There is a patchy but generally thin cover of glacial drift, but a reasonable number of exposures can be found.

The complex is intruded into a regionally-metamorphosed formation of phyllites, with silty bands and beds of quartzite, the 'Dark Argillite' division of the Charlotte Group, probably of Ordovician age (MacKenzie and Alcock, 1946). This group contains minor intercalations of volcanic rocks, and, beyond the limits of the area examined, it passes into schists and gneisses. Adjacent to the norite, on Old, Basswood and Pomeroy ridges, phyllites striking E.N.E. and dipping steeply to the south are exposed; cleavage appears to be parallel to bedding here. A number of large inclusions derived from these rocks are found within the pluton (Fig. 1); since the strike and dip is the same in these as in the surrounding country, they might be regarded as roof-pendants. The age of the batholith as a whole is regarded as Devonian since it intrudes the Silurian Oak Bay Formation, and has yielded pebbles to the Upper Devonian Perry Formation.

The northernmost exposures of igneous rock on Old Ridge reveal a mass of dark rock which proves to belong to the peridotite family. The remainder of the complex is dominated by olivine-norites of various types but the mass is far from homogeneous. It includes, particularly along Hanson Road and in the small stream valley north of the town, banded norites with alternations of anorthositic and troctolitic types—the 'stratified' rocks noticed by the early investigators. It is notable that the strike of the banding, which is nearly vertical, conforms with the Caledonoid trend of the invaded sedimentary formation (Fig. 1). Anorthositic norite is well developed in the neighborhood of Elm Street, and along Cemetery Road; elsewhere, gray rock of gabbroid appearance

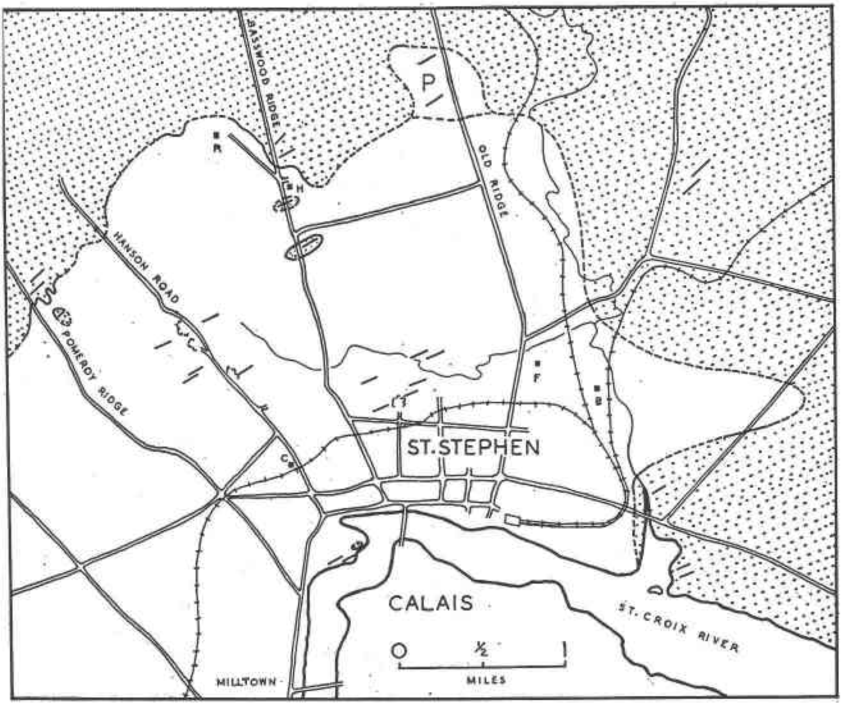

FIG. 1. Geological sketch-map of the St. Stephen district. Stipple—Charlotte Group (pelitic sediments); No ornament—Norite-complex; P, periodotite; R, Rodgers prospect; H, Hall-Carroll prospect; F, Frogtown prospect; B, pit between railroads; C, Cemetery Road excavation. Short black lines indicate strike of banding in norite and bedding in sediments.

prevails. The varieties appear to grade into one another, and exposures are insufficient to justify the mapping of lines between them. The margins of the pluton can be located accurately on Pomeroy, Basswood and Old Ridges, along the road leading north-east from the bridge over Denny Stream, and near the mouth of the stream; the remaining lines are interpolated. Within 100 yards of the margin of the complex, norite gives place to quartz-gabbro rich in hornblende, dark green in color.

Sulphide bodies have been explored at several places. The largest lens so far discovered is on the Rodgers property (R on Fig. 1), west of Basswood Ridge Road, 2½ miles N.N.W. of St. Stephen. According to Low (1930, p. 116) this measures 240 × 112 ft. at surface and has been followed by drilling to a depth of 250 ft.; he estimates the tonnage here at 150,000, containing 45.5 per cent Fe, 24.5 S, 0.9 Cu, 1.5 Ni, 0.1 Co, 0.1 Zn. The long axis of the lens trends E.N.E. On the east side of Basswood Ridge Road occurs a vein-like mass striking north-south on the

Hall-Carroll property; this is 400 ft. long, 10–28 ft. wide (H on Fig. 1). Other occurrences have been tested on the Ganong property, adjacent to the St. Croix river near Milltown, and in pits south-east of Denny Bridge. A showing of sulphides was found in an excavation for a water-main in Cemetery Road in 1935, and magnetic anomalies have been found at numerous other places (*vide* Low 1930, Fig. 2).

South of the area examined, norite gives place to granite. MacKenzie and Alcock (1946) state that the granite cuts a mixed zone of gabbroic and dioritic rocks.

Petrography*

In the account which follows, all determinations of non-opaque minerals are based upon refractive index measurements carried out by the immersion method, which Professor Larsen's work (Larsen, 1921; Larsen and Berman, 1934) has done so much to implant firmly in the technique of petrography.

Harzburgite.—The peridotite exposed on Old Ridge is composed of olivine in rounded crystals up to 2.5 mm. diameter, with subordinate interstitial orthopyroxene and occasional plates of dark brown biotite. Only small amounts of feldspar are present. The composition of the olivine, from refractive index measurements, is Fo_{76}. Closely-spaced veinlets of antigorite with magnetite granules traverse the rock, parallel to the regional E.N.E. strike; these are far more prominent where they cross the olivine than in the pyroxene. In measuring the approximate mode given in Table 1, the chlorite and secondary magnetite were disregarded. The rock is classified as a harzburgite. Other occurrences of peridotite, partly invaded by sulphide mineralization, were noted at the Frogtown prospect (F on Fig. 1) and near a trial pit between the branches of the C.P. railroad.

Olivine-Norite.—The average type of norite is represented by analysis No. 5623 in Table 2 and by a mode in Table 1. The rock, from the St. Croix river cliff, ½-mile west of the railroad station, is a dark gray lustrous phaneride, dominantly composed of a xenomorphic-granular aggregate of plagioclase of composition An_{70-73} (labradorite-bytownite), slightly zoned in places to An_{66} round the margins of the crystals. The average length of the plagioclases is 2.0 mm. Rounded crystals of colorless olivine up to 1.0 mm. diameter are mantled with feebly pleochroic orthopyroxene of composition En_{75} (hypersthene); these also enclose pyroxene crystals. A subordinate amount of clinopyroxene having $n\text{Y}=1.708$ is

* A representative selection of rocks and slices from the area has been presented to the Sliced Rock Collection of the Geological Survey and Museum, London; these carry the registered numbers F.4888, F.5596 to 5659.

TABLE 1. MODES OF ST. STEPHEN ROCKS

(Weight—percentages)

GSM No.	*Rock name* Locality	Modal Plagio-clase	Plagioclase	Olivine	Orthopyroxene	Clinopyroxene	Hornblende	Chlorite, bowlingite, talc	Biotite	Clinozoisite	Ores	Quartz	Calcite	Johann-sen Family
5622	*Harzburgite*, Old Ridge	An_{70}	2	77	18	—	—	*	2	—	1	—	—	428
5604	*Troctolitic olivine-norite*, Thompson Pasture quarry	An_{70-75}	50.6	40.5	2.9	—	—	0.5	0.6	0.5	4.4	—	—	?3312P
5646	*Olivine-hypersthene-gabbro*, N. of Hall-Carroll prospect	An_{70-73}	54.6	21.1	7.8	9.6	5.3	—	0.3	—	1.2	—	—	2312P
5623†	*Olivine-norite*, ½-mile W. of C.P.R. station, St. Stephen	An_{70-73}	55.0	20.1	11.1	8.1	0.7	1.3	0.5	—	3.2	—	—	2312P
5607	*Anorthositic olivine-norite*, W. of Elm St.	An_{71}	75.1	9.3	1.4		12.8		—	—	0.9	—	0.5	2312P
5614	*Anorthositic olivine-norite*, Cemetery Rd.	An_{70}	78.4	12.6	1.0		5.8		—	0.2	2.0	—	—	2312P
5605†	*Anorthositic olivine-norite*, N. end, Elm St.	An_{70}	81.8	2.6	2.3		12.3		—	—	0.8	—	—	2312P
5648†	*Norite-pegmatite*, Basswood Ridge, N. of Hall-Carroll prospect	An_{50-32}	66.0	—	—	—	15.5	9.4	—	—	5.2	1.5	2.4	238

* Measured with olivine and clinopyroxene; see p. 715.

† Chemically analysed rock; see Table 2.

TABLE 2. CHEMICAL ANALYSES AND NORMS OF ST. STEPHEN ROCKS

Analyses	5623 Olivine-norite ½-mile W. of C.P.R. station, St. Stephen	5605 Anorthositic olivine-norite, Elm Street, St. Stephen	5648 Norite-pegmatite N. of Hall-Carroll prospect, Basswood Ridge	4888 Mineralized norites, Hall-Carroll prospect	5655 Mineralized norites, Rodgers prospect
SiO_2	46.14	46.88	48.82	36.26	25.06
Al_2O_3	19.58	28.97	16.93	15.74	7.02
Fe_2O_3	0.64	0.09	0.51	—	—
FeO	8.51	3.01	8.48	—	—
MgO	9.78	3.62	6.08	10.50	4.27
CaO	10.80	14.02	9.42	6.22	2.70
Na_2O	1.58	1.87	3.14	1.58	0.81
K_2O	0.19	0.14	0.15	0.15	0.39
H_2O+	0.65	0.83	0.69	2.84	0.73
H_2O-	0.26	0.27	0.26	1.20	0.20
TiO_2	0.78	0.12	3.39	0.44	0.77
P_2O_5	0.04	tr.	0.48	0.07	tr.
MnO	0.15	tr.	0.24	0.12	0.46
CO_2	tr.	nt.fd.	1.16	nt.fd.	tr.
Fe_7S_8	0.74	—	—	15.03	38.32
$CuFeS_2$	—	—	—	—	1.21
Residual Fe as FeO	—	—	—	8.84	16.70
NiS	nt.fd.	—	—	0.42	1.14
Co	—	—	—	nt. fd.	tr.
Zn	—	—	—	nt. fd.	nt. fd.
	99.84	99.82	99.74	99.41	99.78
Norms					
qu	—	—	1.62	—	—
or	1.11	0.83	0.89	0.89	2.22
ab	13.10	15.77	26.51	13.62	6.81
an	45.87	69.61	31.69	30.30	13.34
cor	—	0.20	—	—	—
di —wo	3.13	—	1.97		
en	1.90 } 6.08	—	1.00 } 3.89		
of	1.05		0.92		
hy—en	8.70 } 13.58	3.63 } 5.54	14.20 } 23.31		
of	4.88	2.01	9.11		
ol —fo	9.73 } 15.85	3.86 } 6.41	—		
fa	6.12	2.55			
mt	0.94	0.14	0.70		
il	1.52	0.20	6.38		
ap	0.10	tr.	1.01		
ca	tr.	—	2.74		
	98.11	98.70	98.74		
pyrrhotite	0.74	—	—	15.03	38.32
water	0.91	1.10	0.95		
	99.76	99.80	99.69		
Normative plagioclase	An_{78}	An_{81}	An_{54}	An_{69}	An_{67}

Analyst, W. H. Herdsman, Glasgow, 1939.

associated with the hypersthene. Rod-like inclusions of an opaque mineral form patches in both pyroxenes. Small quantities of amphibole, pleochroic pale brown to yellow (further discussed below), and of biotite have developed at the expense of the pyroxenes. Scattered crystals of magnetite and of pyrrhotite are present.

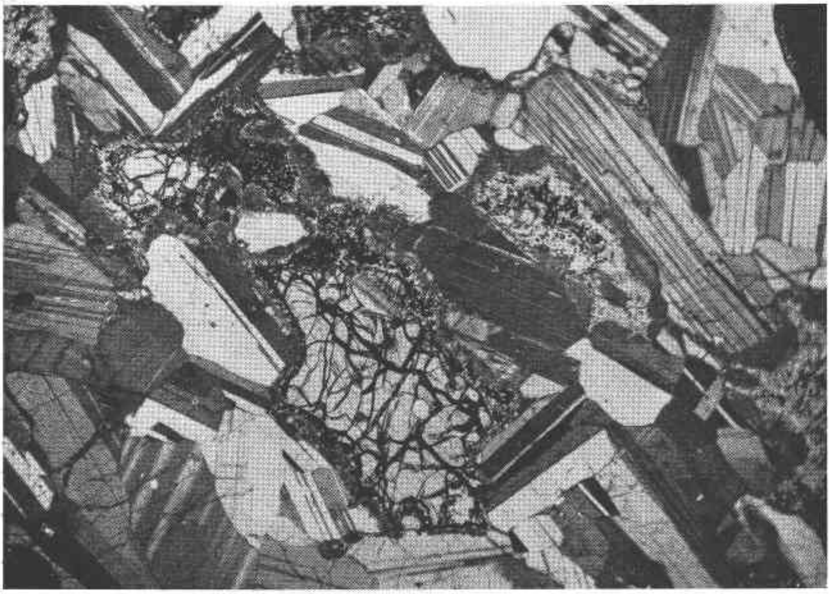

FIG. 2. Photomicrograph of thin section of anorthositic olivine-gabbro, to show kelyphitic coronas round olivine crystals. (Crossed nicols, ×24) West of Elm Street, St. Stephen.

In the olivine-norites (including the special varieties discussed below) the remarkable feature is the constancy in composition of the olivine. Determinations on material from all parts of the area show a divergence from $nZ = 1.695$ (indicating a composition Fo_{66}) only within the limits of error of the immersion method ($\pm .003$, equivalent to a maximum error of 3 per cent Mg_2SiO_4). It will be noted, however, that the olivine in the norites differs in composition from that in the harzburgite. There is little divergence from An_{70} among the feldspars of the norites (excluding the quartz-gabbros, which contain more sodic feldspars) though here, since the refractive index curves are flatter, there is a greater possibility of error. The orthopyroxenes, on the other hand, exhibit wide variations, the range being from $nZ = 1.675$ (enstatite, En_{90}) in troctolitic norite from the north-western quarry in Hanson Road, to $nZ = 1.730$ (iron-rich hypersthene, En_{60}) in inclusions within the Rodgers pyrrhotite body. The magnesian types are colorless, but at a composition of En_{75} pleochroism becomes appreciable both in thin sections and powders.

A few examples of rocks in which augite is more abundant than orthopyroxene have been found; a mode illustrative of one such rock is given on p. 716. Such rocks, properly classed as olivine-hypersthene gabbros, appear to be subordinate to olivine-norites in bulk.

Troctolitic and anorthositic olivine-norites.—Banding in the norites

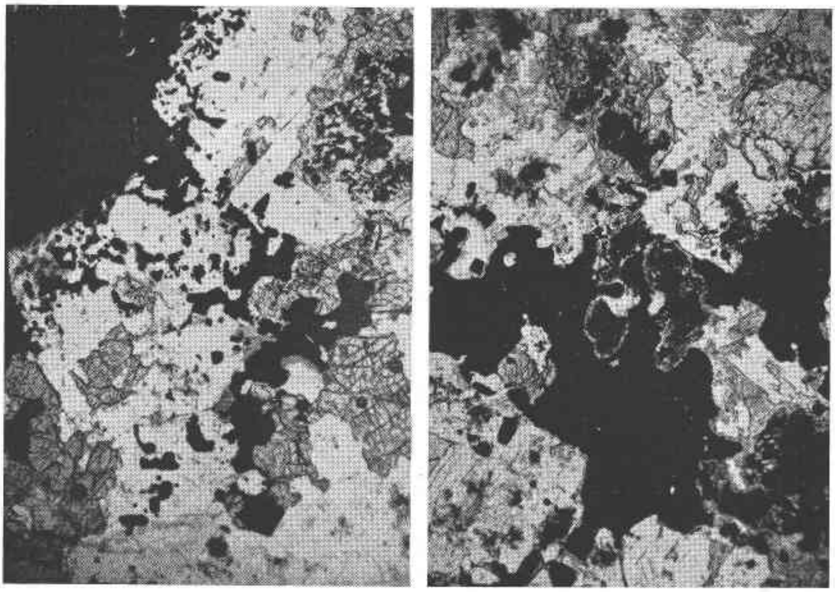

FIG. 3. Photomicrographs of thin sections of olivine-norite, to show replacement by magnetite and sulphides. In the left-hand photograph, the micropegmatite-like margin of a mass of pyrrhotite is shown ,and the preferential replacement of orthopyroxene by sulphides (Ordinary light ×30). In the right-hand photograph, partial replacement of rounded olivines by magnetite, surrounded by massive pyrrhotite is seen. (Ordinary light ×39). Rodgers prospect, St. Stephen.

takes the form of rhythmic alternations of concentrations of mafic constituents, particularly olivine, and felsic minerals. It ranges from barely perceptible streaking to the development of separate layers of melanocratic and leucocratic rocks. The extreme melanocratic type may be classified as troctolitic norite; a typical mode is given in Table 1. The rock is rich in rounded crystals of colorless olivine up to 2 mm. diameter, mantled with a small amount of enstatite and enclosed in a mosaic of coarse bytownite. Rocks rich in pyroxenes are rare and only one example was found.

The leucocratic rocks are largely composed of fresh labradorite-bytownite and these are classified as anorthositic norites. Such rocks not only enter into the banded portions of the complex, but also form substantial separate areas, for example between Elm Street and Cemetery Road. They are pale gray phanerides, mottled with evenly-scattered darker gray clots of ferromagnesian minerals, mainly olivine. None of the specimens studied show the achievement of true anorthositic composition, with over 90 per cent plagioclase; the nearest example carries 81.8 per cent. The olivine occurs as rounded crystals, enveloped by complex kelyphitic rims which are further described below. The plagioclase, which is coarsely twinned, shows neither zoning nor automorphism. The maximum crystal size is about 3 mm.

Relations with the invaded rocks; xenoliths.—The country rock into which the norites and harzburgite were intruded consists of quartz-chlorite-muscovite phyllites. Sliced specimens from near the mouth of Denny Stream, from Basswood Ridge, and also from Valley Road, remote from the norite, all indicate a similar metamorphic condition. The constituents include pale green, low-birefringent, optically negative chlorite, muscovite in flakes up to 0.05 mm. long, quartz, a little alkali feldspar, and evenly-scattered granules of magnetite, hematite and 'leucoxene.' The rocks are finely laminated; some bands being largely quartz-silt with a little chlorite; others being almost exclusively muscovite, well-oriented parallel to the bedding. All three main constituents may occur together in a band. The micaceous layers in some instances show small-scale drag-folding not exhibited by adjacent competent silt layers. The nearest exposure to the norite on Basswood Ridge failed to show any higher grade of metamorphism, and some of the xenoliths in the norite are in a similar condition.

Within the norite, however, on Basswood and Pomeroy Ridges, more intense metamorphism is exhibited by the large included masses of country rock. The micaceous minerals have been partially or wholly converted into deep brown biotite and the quartz has been recrystallized to a decidedly coarser grain-size. In the larger included mass on Basswood Ridge, abundant cordierite makes its appearance and certain bands carry hypersthene (En_{70}) associated with biotite showing $nZ = 1.640$, and a mosaic of quartz. The new ferromagnesian constituents in these free-silica hornfelses fail, in general, to maintain the preferred orientation of the chlorite and muscovite in the rocks from which they have been derived, but the lamination is preserved and evidently represents appreciable variations in composition. Small separate xenoliths of quartz-biotite-hornfels are found as far south as the cliffs of the St. Croix river between St. Stephen and Milltown. The further alteration of these hornfelses is considered in the next subsection.

Dark, fine-grained xenoliths from the St. Croix exposures prove to consist of pyroxene-granulite, composed of slender calcic labradorite crystals, with abundant drop-like granules of pale-green augite and magnetite. The close similarity of these rocks to the granulites in the gabbros of Skye (Harker, 1904, p. 115) and Ardnamurchan (Richey and Thomas, 1930, p. 230) suggests that they represent fragments of basic lavas incorporated in the norite. Such xenoliths are far less common than those of biotite-hornfels. A few examples have been found of diabase-like xenoliths having normal rather than granulitic pyroxenes, and carrying some olivine. It is not clear whether these represent a more advanced stage in the metamorphism of the granulites, or an early magmatic phase of the norites, broken up and incorporated in the main intrusion.

Doubt also attaches to the origin of angular white zenoliths up to 6 inches on the side, which occur in the Basswood Ridge road-cutting and elsewhere. The principal constituent is plagioclase of more sodic composition than in the adjacent norite (generally labradorite), forming granular aggregates of equidimensional crystals of 0.1 to 0.2 mm. diameter, engulfed in coarser plagioclase which also encloses crystals of dark green pleonaste up to 0.5 mm. long, and aggregates of white mica. A few crystals of amphibole and biotite are present in some examples, and clinozoisite occurs in dusky patches. Surrounding such inclusions there appears to be in all cases a zone, up to 5 mm. wide, exclusively composed of bytownite. It appears most probable that these rocks represent silica-poor hornfelses, but the necessary links with the country rock have not been found.

Marginal modifications of the norite.—Along the contact of the complex with the phyllites, and extending up to 100 yards from the contact, the norite gives place to quartz-hornblende-gabbro. Green and greenish-brown hornblende, both in coarsely crystalline and acicular varieties makes as much as half the rock. The composition of the amphibole is variable, as indicated by refractive index measurements ranging from $nZ'=1.660$ in acicular types to 1.680 in massive varieties. Ferriferous biotite is also generally present, with nZ ranging from 1.635 to 1.650. The amphibole may contain cores of pyroxene and, occasionally, of olivine and the coarse type appears to have originated mainly from these minerals. The acicular type has also extensively replaced plagioclase. The feldspar is labradorite, appreciably more sodic than the feldspar of the norites. Quartz forms coarse interstitial areas. Rarely, a little micropegmatite is associated with it, and in one example, soda-orthoclase was found.

Similar rocks surround the large xenoliths or pendants of hornfels and here a stage representing the feldspathization of the hornfels, or the mingling of constituents derived from the hornfels with crystallizing feldspars can be recognized. The size of the biotite crystals as developed in the mixed rock is decidedly greater than in the hornfels and quartz is again the final product of crystallization. On the other hand the plagioclase—ranging in composition from An_{56} to An_{70}—is finer grained than in the norite, and of more obvious lath-shaped habit. Occasional larger crystals, comparable in size with those in the norite, appear as this rock is approached. Hornblende may be a major constituent. It is noticeable that both the marginal quartz-gabbros and those surrounding xenoliths contain apatite, a mineral rarely seen in the norites.

Adjacent to the pyroxene-granulite xenoliths the norite contains many inclusions, particularly of rounded augite granules. Coarse labradorite crystals along the margins extend from the norite into the xenoliths, and are of the nature of porphyroblasts in the latter. The norite itself is poor in olivine and unusually rich in hypersthene; it also carried more biotite than usual.

Norite-pegmatite; Aplites.—Small veins of leucocratic pegmatite are occasional features of the norites. A detailed study of one of these, from the road cutting on Basswood Ridge, showed that it consists of coarse plagioclase zoned outwards from about An_{50} to An_{32}. Green amphibole, also distinctly zoned with nZ' varying from 1.664 to 1.660, coarse biotite, partly altered to chlorite, quartz, calcite ($nO=1.657$) and apatite are also present. Ilmenite forms large crystals in the rock. An analysis of this rock is given in Table 2. Its interest lies in the fact that it indicates a trend towards the concentration of soda and of titanium in the residual liquors, but shows no concentration of potash.

Two aplite veinlets, respectively 1 and 3 inches wide, were investigated. Both proved to be microgranodiorites composed of zoned oligoclase, perthitic orthoclase, quartz, biotite and apatite. It seems more likely that these are associated with the granitic phase of the batholith than with the norites.

Hydrothermal alteration of the norite.—The descriptions given of the olivine-norite, and its troctolitic and anorthositic varieties, which together make up the greater part of the complex, will have made it clear that they are for the most part in a fresh condition, fresh olivine, for example, being the rule rather than the exception. Nevertheless, alterations yielding minerals containing the hydroxyl group, here described as hydrothermal, played a minor part in the evolution of these rocks. Alteration of the olivines takes several forms. The commonest is the development of a mineral showing perceptible pleochroism X, pale pinkish brown, Y, Z pale green; optically negative with low 2E, $nZ=1.589$, birefringence 0.03, one good cleavage, parallel extinction. This is tentatively assigned to bowlingite; the similarity of the mineral to talc in many of its properties (though not, of course, its color) may be noted. In this type of alteration, the olivine is generally pseudomorphed by the bowlingite together with a little magnetite. Fine-grained amphibole and antigorite also occur as pseudomorphs after olivine.

In the anorthositic norites, kelyphitic coronas are developed around fresh olivine crystals. These generally show an inner rim, next to the olivine, of low-birefringence, optically positive chlorite, probably pennine; and an outer rim of tremolite ($nZ'=1.595$) adjacent to the plagioclase. No doubt the lime for the tremolite was derived from the feldspar, the magnesia from the olivine. Talc is developed in association with some of the coronas.

The orthopyroxenes are converted in places into amphibole for which the following data is representative: $nZ=1.689$, birefringence 0.026, Z(pale brown) $>Y>X$(yellow), $Z\wedge c=13°$, 2V near 90°. This data would be consistent with cummingtonite and it is quite likely that the lime-content is small. Other amphiboles, however, including those in the analysed olivine-norite, must carry appreciable amounts of lime in view of the difference between the normative and modal plagioclase. Fibrous amphiboles, though not common except in the quartz-gabbros, are occasionally found. In a few instances in the norites, actinolite with $nZ'=1.633$ was noted. At least part, and probably a large part of the crystallization of the amphiboles took place after the consolidation of the norites. Joint faces in a quarry on Hanson Road yielded stellate clusters of green hornblende with crystals up to 3 inches long, showing $nZ'=1.652$.

In the marginal quartz-gabbros it may be suggested that the formation of amphiboles and biotite was promoted by the incorporation of hydroxyl-bearing minerals from the country rock. It is unlikely, however, that the amphibole remote from the margins owes its origin to the same cause and there is similarly some biotite which must be assigned to the late stages of consolidation of the norite. This biotite is less ferriferous than that in the hornfelsed and marginal rocks, as indicated by its range of of refractive indices nZ between 1.608 and 1.612.

Sulphide Mineralization.—Pyrrhotite, in small amounts, occurs in all the rocks of the complex, including the hornfels xenoliths. Substantial concentrations are confined, as far as is known at present, to the localities listed on p. 717. The evidence is quite clear, as Dickson (1906) first demonstrated, that these concentrations were formed by replacement of the igneous rocks, textural features of which are preserved in the sulphides.

Polished sections of material from the Rodgers and Hall-Carroll prospects show, in doubly polarised light, that the pyrrhotite is a xenomorphic-granular aggregate of crystals ranging from 0.03 to 1.0 mm.

diameter. It encloses rounded magnetites (in some instances with plates of specularite) up to 0.5 mm. in diameter; these are cut by pyrrhotite veinlets. Intergrown with the pyrrhotite there are irregular groups of pentlandite crystals (soft, brass yellow, isotropic, showing cubic cleavage and triangular pits) and of chalcopyrite. Although elongate segregations of these minerals occasionally occur, the balance of evidence favours the view that they were deposited with the pyrrhotite, later than the magnetite.

Magnetite is only a minor constituent in the norites, occurring chiefly as a replacement of olivine associated with bowlingite or antigorite. In the mineralized ground, all stages may be found from incipient to complete replacement of olivine by magnetite, and there is no doubt that the rounded masses of magnetite in the massive sulphide bodies represent former olivines. When replacement of the olivine is effected by a mixture of antigorite or amphibole and magnetite, the latter mineral acquires the feathery texture to which Dickson has referred.

The sulphide mineralization was accompanied by the conversion of the silicates of the norite to hydroxyl-bearing minerals, chiefly actinolitic amphiboles, clinozoisite and chlorite. In the less intensely mineralized rocks, adjacent to the massive sulphide bodies, the pyrrhotite is surrounded by narrow zones of these minerals. There is some evidence of preferential attack by the sulphides on pyroxenes and amphiboles; certainly the olivines, whether altered to magnetite or not, were partially or wholly avoided. This type of alteration is illustrated by analysis 4888, Table 2; as compared with the norites, the increase in magnesia (in chlorite and amphibole) and of combined water will be noted. There is also a rise in the soda/lime ratio, representing the partial albitization, also evident under the microscope, of the feldspars. In this case, no rise in potash is found.

Within the sulphide lenses, the hydroxyl-bearing minerals have largely been eliminated by the advance of sulphide-replacement, and all that remains from the norite is a series of relics, mainly of anhydrous silicates. As at Sudbury, therefore, specimens can be obtained showing pyrrhotite corroding and replacing 'pyrogenic' silicates, and also of the sulphide accompanied by hydroxyl-bearing silicates. The rock analysed from the Rodgers prospect (Table 2, 5655), represents an approach to the massive sulphide stage. Combined water in this is no higher than in the normal norite; the feldspars are again albitized and here there is more potash than usual. The potash appears to be due to biotite which may represent the remains of hornfels xenoliths; no potash feldspar or sericite was found. Campbell and Knight (1907) give the following mineral sequence for St. Stephen: (1) Magnetite (2) Silicates (3) Sulphides. The present study suggests that (1) and (2) should be transposed.

Post-mineralization effects.—At the Rodgers prospect, a narrow north-south dike cuts through the sulphide body (*vide* Low, 1930, Fig. 3). This proves to be composed of elongate olive-green hornblendes which, with biotite, form half the rock, the remainder being made up of zoned andesine-labradorite (An_{45-55}), about 3 per cent quartz, calcite, apatite and a little pyrrhotite. This is classified as biotite-spessartite; no other example was found.

Shear-planes and joints cut the massive sulphides; on some of the former and on shear-planes in the norites, asbestiform minerals including anthophyllite and chrysotile are found. Data for an anthophyllite from Hanson Road quarry shows $nZ=1.646$, indicating, from the curve given by J. C. Rabbitt (1948, p. 295), about 13 per cent $FeO+Fe_2O_3+TiO_2+MnO$. Another anthophyllite, from the Hall-Carroll prospect, showed $nZ=1.629$. Brown-stained portions in both examples showed higher refractive indices. The crysotile has $nZ=1.556$ at the trial pit between the two branches of the C.P.R.; here, remains of olivines have also been replaced by this mineral.

Petrology

The following petrological conclusions are drawn from the facts given:—

1. The constancy in composition of the olivine and bytownite suggest separation of these minerals from a magma of uniform composition. They did not, however, necessarily separate *in situ*.

2. The banding in the norites, parallel to the bedding and cleavage in the invaded rocks, cannot have been inherited from the sediments by metasomatism if argument (1) is accepted. In support it may be stated that where the interaction of the igneous complex and the sediments can be studied, mixed rocks rich in hydroxyl-bearing minerals are found; and that the large included hornfels masses showing bedding are surrounded by norites which fail to show banding. The banding requires further examination in the light of the work of J. W. Peoples (1936), L. R. Wager and W. A. Deer (1939) and F. Stewart (1947). In this area, where the banding is conformable to the bedding in the country rock, the hypothesis that the bands originated as horizontal layers prior to the regional folding might prove acceptable.

3. The magma was characterized by (i) low potash-content, a feature maintained throughout the rocks investigated; (ii) low water-content. Reactions around the margins of the intrusion involving chlorite and muscovite from the pelitic sediments augmented the available (OH) and led to the formation of hornblende- and biotite-bearing gabbros.

Feldspars formed in the mixed rocks were of more sodic composition than those in the norites, and were locally accompanied by a little orthoclase. Quartz from the pelitic sediments was dissolved and redeposited interstitially in the marginal gabbros. Apatite was similarly derived.

4. The low grade of metamorphism of the sediments adjacent to the complex may be ascribed either to a comparatively low magma- (or mush?)-temperature, or to the low content of volatiles in the magma, or both.

5. Incorporation of silica-rich hornfels may have contributed to the orthopyroxene-content of the norites, as Read (1935) demonstrated in the case of the Haddo House (Aberdeen) norite. The great variations in composition of orthopyroxene would be adequately explained on this basis. From this stage, crystallization *in situ* must be postulated for the main norites.

6. Mild hydrothermal alteration in the inner parts of the complex led to the development, by metasomatism in the solid, of cummingtonite from orthopyroxene; of tremolite from plagioclase; of bowlingite, antigorite, talc and pennine, with magnetite, from olivine. These changes probably involve addition of (OH) with only very local migration of other constituents.

7. Small pegmatites indicate a trend towards relative concentration of soda and titanium in residual fluids.

8. More intense hydrothermal alteration, perhaps due to residual fluids from lower parts of the complex, accompanied the very localized development, by metasomatism, of massive magnetite-pyrrhotite-pentlandite-chalcopyrite lenses. It is suggested that sulphidization eventually outstripped (OH)-metasomatism. The sulphide bodies are considered to be of 'pneumotectic' character (L.C. Graton and D. H. MacLaughlin, 1917).

9. A dike of biotite-spessartite, cutting through a pyrrhotite lens, represents the dying stage of basic magmatic activity here. Anthophyllite and chrysotile were formed on post-sulphide shear-planes.

10. Small aplites are believed, though not proved to belong to later granitic activity in the pluton.

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