Geological and Petrographical Studies of the Sudbury Nickel District (Canada).

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4. Geological *and* Petrographical Studies *of the* Sudbury Nickel District (Canada). By T. L. Walker, Esq., M.A. (Communicated by J. J. H. Teall, Esq., M.A., F.R.S., Sec. G.S. Read November 4th, 1896.)

[Abridged.]

Contents.

I. Introduction.

The town of Sudbury is situated in Northern Ontario, 442 miles from Montreal on the transcontinental line of the Canadian Pacific Railway. When this railway was constructed some eight or ten years ago, the name Sudbury was given to a small station which was afterwards selected for the eastern terminus of the branch railway that follows the northern shore of Lake Huron and crosses the St. Mary River at Sault Ste. Marie. It is about 40 miles from the north-eastern shore of Lake Huron.

Shortly after the construction of the railway, considerable deposits of chalcopyrite were discovered in the neighbourhood, and an American company was organized to work them. Thus it was that Copper Cliff Mine was opened up for copper, although along with the chalcopyrite large quantities of nickeliferous pyrrhotite occurred. The pyrrhotite was considered worthless, as it was not known to contain nickel till the mine had been in operation for some little time, and sales had been made of the products. After the accidental discovery of the value of the pyrrhotite as a nickel ore, there was much prospecting in the district for nickel-deposits. This continued till 1891, by which time scores of nickel-deposits had been located. At that time the world's annual consumption of metallic nickel was not more than 1500 tons, and hence it was a more difficult task to dispose of nickel properties at remunerative prices than it was to discover them. For this reason, prospecting for nickel was abandoned in this region, though it is quite probable that, should a demand for larger quantities of nickel arise, many more deposits will yet be discovered.

The earliest geological descriptions of the country in the immediate vicinity of Sudbury were published by Selwyn in 1884. In 1888 Bonney published an account of the Huronian rocks exposed

in the cuttings of the Canadian Pacific Railway in the neighbourhood of Sudbury. During the seasons of 1888, '89, and '90, Bell and Barlow were appointed by the Canadian Geological Survey to explore the district. A collection of rocks was sent by Bell to the late G. H. Williams, whose petrographical studies were published along with Bell's report. During the summer of 1890 the late Baron von Foullon, of the Austrian Geological Survey, spent a few weeks in the district, and directed his attention particularly to the determination of the relative ages of the different rocks. A full statement of the literature bearing on the subject is appended (§ VIII. p. 65). I beg to acknowledge my indebtedness to the writings of all who have studied the geology of the Sudbury district, especially to the papers of Adams, Bell, Barlow, Bonney, von Foullon, Garnier, and G. H. Williams. Vogt's excellent descriptions of the Norwegian nickel-deposits and associated rocks have been freely consulted, as in many respects these descriptions are quite accurate when applied to the Sudbury district.

The nickel district is included in the great belt of Huronian rocks which extends from the northern shore of Lake Huron north-eastward to Lake Mistassini. In the neighbourhood of Sudbury this belt is barely 25 miles wide, and consists of quartzite, amphibolite, mica-schist, phyllite, volcanic breccia, and grauwacke. Inliers of later eruptives form a large part of the belt, and it is in connexion with one class of these that the nickel-deposits occur. The country north-west and south-east of the belt of Huronian rocks is composed of coarse granites and gneisses which are regarded as of Laurentian age.

The whole of this part of Canada has been subjected to glacial action, the general direction of ice-movement having been from north-east to south-west. The rocks in many places present well-polished surfaces, particularly where the protecting covering of clay, sand, or gravel has been only recently removed, as in railway-cuttings and along lake- and river-banks. The most lasting work of glacial agency is seen in the hollowing-out of innumerable depressions, which are now occupied by lakes and rivers. Archæan districts in Canada are characterized by innumerable rocky lakes with clear waters and swift eddying streams.

II. The Gneiss-Formation.

The larger part of Northern Ontario is occupied by gneisses of various kinds. In the immediate vicinity of Sudbury these rocks are not observed, though they form almost endless tracts on both sides of the Huronian belt. Good exposures, which are easily reached, occur in the cuttings of the Canadian Pacific Railway, near Wahnapitae to the south-east, and about 3 miles west of Onaping to the north-west. Besides these gneisses, which may be regarded as Laurentian, there are gneissoid rocks geographically included in the Huronian belt, but as these are of very much later origin, and not true gneisses, it is proposed to deal with them in a later section.

(i) The Gneisses near Wahnapitae Station.

These rocks are well bedded, and show considerable folding on a large scale. Biotite is by far the most prominent constituent. Over large areas reddish almandine-garnet is so common that the Wahnapitae rocks may be designated 'garnetiferous biotite-gneiss.' The garnets vary from $\frac{1}{8}$ to $1\frac{1}{4}$ inch in diameter, and are often so abundant as to constitute 20 per cent. of the rock. When in micaceous bands they are crystallized in rhombic dodecahedra ∞O, while when in quartzose or felspathic bands they are always icositetrahedra $2\,O\,2$. As a rule, garnets are inclined to crystallize in rhombic dodecahedra when in schistose or basic bands, while when in acid or granular bands there is a tendency to take the form of icositetrahedra.

The microscope shows that the biotite is strongly pleochroic and nearly uniaxial. It occurs as comparatively large independent individuals, and never forms continuous films composed of innumerable small individuals. The biotite is sometimes altered to chlorite. Muscovite is occasional. The quartzes abound in liquid inclusions, which are often characterized by moving bubbles or small cube-like crystals. Felspar plays an important part, and is frequently perthitic or microclinic. Kyanite is often abundant, and presents in rock-sections long, highly-polarizing individuals which generally, but not always, conform to the schistosity. Inclusions of quartz and felspar are quite common. The colour is different in different individuals, and even in different parts of the same individual. Some are water-clear, while others are water-clear with irregular sky-blue flecks. No twinning could be detected. Sillimanite is frequent on slickensides. The long, colourless, acicular crystals show the effect of pressure in being broken into large numbers of short prismatic fragments which are drawn apart, so that the disjointed crystal is about twice as long as the original crystal. Zircon in rounded grains is frequent, and seems to be largely confined to the neighbourhood of biotite. When the zircon-grains are included in the biotite, they are usually surrounded by pleochroic areas ('pleochroitische Höfe').

(ii) Gneiss near Onaping Station.

The gneiss exposed west of Onaping Station is largely composed of quartz and felspar, which form pinkish-white bands: these alternate with comparatively small bands of biotite. The Onaping gneiss is thus very much lighter in colour than the gneiss at Wahnapitae. The microscope shows that these rocks are true gneisses and not crushed granites. Biotite occurs in large individuals, whose prismatic sections show a well-developed system of partings which form a cross-hatching, probably the result of pressure. The gliding-plane is apparently a pyramidal face, as has been proved to be the case for large mica-individuals by Tschermak. Biotite is sometimes changed to an aggregate of chlorite, epidote, and sphene. Specimens collected farther south-west on the same gneiss-terrane contain almost equal quantities of biotite and muscovite, both of which are well preserved.

III. The Huronian Rocks.

These are chiefly confined to the Huronian belt, which in the neighbourhood of Sudbury is about 25 miles wide. Inliers of different kinds are numerous, but these will be described in a later section. Quartzite, grauwacke, mica-schist, phyllite, and altered volcanic breccia are the chief constituents of the Huronian complex. They have all suffered extensive metamorphism, so that it is generally difficult to speak definitely as to their origin. Those which have been derived by the disintegration of still older rocks are to be regarded as among the oldest-known sediments. It is possible that some of the above rocks have been derived from acid tuffs, which in some cases may have been deposited in the primeval sea, as suggested by the frequently perfect stratification. Some may have been derived by the devitrification of flows of glassy, occasionally porphyritic eruptives. Metamorphism has advanced so far that the early history of these rocks is only very imperfectly revealed. All of the above-mentioned sources have doubtless contributed to the formation of the Huronian strata of the Sudbury district.

(i) Quartzites.

In the immediate vicinity of Sudbury, numerous exposures of these rocks are observed. In general the texture is very fine, the stratification obscure, and the colour ashen-grey. The microscope shows that the quartz-grains interlock as if much secondary enlargement had taken place, although no outline of original grains could be detected. Grains of perthitic felspar and scales of muscovite are mingled sparingly with the grains of quartz. Small clusters of brown mica and rounded spots of chlorite are often seen in thin sections. The general strike is N. 30° E. A short distance north of Sudbury, on the way to Blezard Mine, an evenly-stratified quartzitic rock occurs. Narrow bands of a few millimetres in width may be often followed for some score yards. A microscopic examination shows the presence of much muscovite and numerous small colonies of chlorite. This rock is also well exposed along the road to Copper Cliff Mine, about a mile from Sudbury. West of Sudbury, along the Canadian Pacific Railway, the quartzites are, as a rule, very thickly bedded, while in some cases bedding is scarcely discernible.

South-east of Sudbury, along the rocky shores of Ramsay Lake, conglomeratic phases of the above quartzites occur. The pebbles are in the main of reddish granite and vary much in size. As a rule, the south-eastern side of the Huronian belt is composed of the quartzitic rocks just described. The conglomeratic portions are undoubtedly derived from still older Archæan rocks, while the evenly-bedded, very micaceous strata may represent altered acid tuffs which were deposited in shallow water. Bonney has suggested that some of the very fine-grained, indistinctly-bedded muscovite-quartzites may have been derived by devitrification of acid glassy or porphyritic rocks.

Exposures of highly-altered quartzite occur south of the Stobie Mine, and also on the main line of the Canadian Pacific Railway, 1¼ mile west of Sudbury. At the former place, the altered rock becomes quite granitic in composition, and gneissoid in structure. The microscope shows that the component minerals are quartz, felspar, biotite, and a little muscovite. Quartz-grains abound in fluid inclusions, are irregular in outline, and generally interlock. Muscovite forms large separate individuals, while biotite usually forms approximately-parallel connected aggregates of small scales. The rock exposed on the railway west of Sudbury is of medium grain and peculiarly mottled: pale pink, roundish spots, from 1 to 4 inches in diameter, dapple a groundwork of a dark grey colour. On closer examination, it is seen that no sharp boundaries exist between the portions of different colour, and a microscopic examination shows that there is no important mineralogical difference. Gneissoid structure is altogether wanting. Crystals and grains of reddish garnet occur in addition to the minerals present in the rock south of Stobie Mine. Considering the mineralogical composition of these rocks, they may be referred to as biotite-granite. Bell has shown that these highly-altered clastics constitute a belt ½ mile wide and 6 miles long, extending from near the Stobie Mine south-west nearly to Copper Cliff Mines. Naturally, only a very impure quartzite could give rise to such rocks as these. We know very little as to the causes of this extreme and apparently selective metamorphism. Rocks of granitic composition and structure, when formed by the regeneration of clastics, may be called 'regenerated granites.' There is reason to believe that this is a more fruitful source of granitoid rocks than has been previously acknowledged.

(ii) Mica-Schists.

In the immediate vicinity of Sudbury these rocks, though occasionally present, play a very subordinate part. They generally dip at high angles, and are more frequent towards the centre of the Huronian belt. A very narrow band of silvery grey mica-schist crosses the railway about ½ mile east of Murray Mines. In thin sections the foliation is very distinct. Muscovite forms a network which surrounds the quartz-grains. Immediately east of Worthington Station a similar rock is exposed in the railway-cuttings. Farther south-west the Huronian belt is much richer in mica-schists, which are often hornblendic and staurolitic. Between Blezard and Stobie Mines a dark, compact, schistose rock occurs, which the microscope shows to be a hornblende-epidote-schist; it is perhaps geologically an equivalent of the mica-schists.

(iii) Phyllite.

This rock is very closely associated with the mica-schists, and may be examined in the railway-cuttings 3 miles east of Worthington Station. The rock dips at high angles, and is purple-brown in colour. On the cleavage-surfaces small yellowish-brown specks are observed which the microscope shows to be sagenitic aggregates of rutile-crystals: these are fairly transparent, and so large as to give polarization-colours resembling those of zircon.

(iv) Clay-Slates.

These constitute an important member of the Huronian complex. They may be examined ½ mile west of Rayside Station, and also a short distance north of White Water Lake. In the former place they are in contact with the nickel-bearing rocks, and close to the junction the schistosity has quite disappeared. They are ashen-grey, drab to nearly black in colour, and probably represent detritus deposited in the deeper seas of the Huronian period.

(v) Volcanic Breccia.

The western portion of the Huronian belt in the Sudbury district is occupied by a trough which is composed of the younger Huronian rocks. This trough extends nearly from Lake Wahnapitae south-westward to the township of Trill, a distance of over 30 miles. The greatest width is a little over 8 miles. The central part of the trough is occupied by evenly-grained grauwacke, while the margin is composed of a highly-altered volcanic breccia. One of the most accessible exposures of this breccia is on the northern shore of Whitson Lake, where it is in contact with the nickel-bearing eruptive. The colour is ashen-grey, the stratification distinct, though interrupted and lumpy, and the strike is N. 70° E. The microscope discloses the breccia-structure. The volcanic fragments are quite angular, and sometimes show flow-structure, though they have been generally replaced by aggregates of secondary minerals —chlorite, quartz, felspar, muscovite, and calcite. Glass could be seen neither in the fragments nor in the matrix. An analysis of the breccia north of Whitson Lake gave the following results:—

SiO_2	59·93	°/₀.
Al_2O_3	12·12	„
FeO	10·56	„
MnO	trace	
CaO	4·49	„
MgO	5·19	„
Na_2O	3·80	„
K_2O	0·97	„
Loss by ignition	1·57	„
Total	98·63	„

There are also good exposures of this rock along the north-western border, about 1½ mile south-east of Onaping Station.

(vi) Grauwacke.

The central portion of the trough of younger Huronian rocks is occupied by an even-grained, ash-coloured, quartzose rock, in which conglomeratic fragments may be detected with the naked eye. This is the youngest member of the Huronian complex, and, as it is never cut by the nickel-bearing rocks, I am inclined to regard it as later than these. There is good ground for looking upon the nickel-bearing rocks as younger than the volcanic breccia, and hence the conclusion that the nickel-bearing rocks are of Huronian age, and that they occupy a position lying chronologically between the volcanic breccia and this youngest member. It may be mentioned, however, that Bell and Selwyn are inclined to regard the grauwacke as Lower Cambrian, although no fossils have been found in it.

Good exposures occur at several points along the railway, especially at Chelmsford and Larchwood Stations.

IV. The Nickel-bearing Rocks.

(i) General Observations.

These rocks have attracted much more attention than the other rocks of the district. The discovery of areas characterized by extensive deposits of nickel ores gave employment to large numbers of explorers from 1887 to 1891. It was soon remarked that valuable deposits of copper and nickel ores occurred only in connexion with greenish-coloured rocks of medium texture, which were conveniently referred to as trap, diorite, or greenstone. Early microscopic examination of the rocks in the immediate vicinity of the nickel-deposits showed that they were composed in general of hornblende and plagioclase, and in smaller proportions of quartz and biotite, with magnetite and apatite as accessories. Thus the microscope confirmed in a measure the prospectors' name 'diorite,' but it also showed the probability of the secondary nature of the chief constituents, and so the original nature of the country-rock of the nickel-deposits continued to be a matter of doubt. As the hornblende was probably derived from one of the members of the pyroxene group, the original rock was doubtless one of the gabbro family.

In the published descriptions these rocks are referred to as diorite, uralitic diorite, gabbro-diorite, and even occasionally as diabase. This uncertainty is in a measure accounted for by the fact that most of the specimens studied microscopically were collected quite close to the nickel-deposits, where the rock is as a rule completely altered, though in other parts of the 'greenstone' area the metamorphism has seldom advanced so far, and in some places the rock is practically unaltered.

It will be seen that the nickel-bearing rocks, taken as a whole and considered geologically, include not only these greenstone areas but also considerable areas of gneissoid and micropegmatitic granite, which cannot be genetically separated from the greenstones. The geological map of the Sudbury district published by the Canadian Geological Survey contains nearly one hundred areas of greenstone. We will confine our attention to a very small number of these nickeliferous eruptives.

The nickeliferous rocks are included in or adjoining the Huronian belt already described. They commonly form long elliptical areas whose longer axis is more or less parallel to the stratification of the Huronian rocks. The largest of these areas extends from the township of Garson south-westward into the township of Creighton, having a width of nearly 4 and a length of at least 25 miles. It is crossed by the Canadian Pacific Railway between Murray and Rayside Stations. The area second in size is described by Bell as extending from the township of Lavack south-westward to the township of Trill. Its length is at least 18 miles, and its width between 3 and 4 miles. Onaping Station is situated near the south-eastern border of this eruptive area. As the former eruptive is well exposed in the vicinity of Whitson Lake, it will be convenient to refer to it as the Whitson Lake eruptive. For a similar reason, the second eruptive area will be referred to as the Windy Lake eruptive.

(ii) The Whitson Lake Eruptive.

The length of this area has been very moderately stated above; there is good reason for regarding it as much greater, and possibly connected with other nickeliferous areas which are now mapped as separate eruptives. The best exposures are to be found along the shores of the lakes lying within its bounds, and in the cuttings of the Canadian Pacific Railway. Along its north-western boundary it is flanked by the volcanic breccia previously described. It includes three parallel areas, which were mapped by Bell as greenstone, granite, and Huronian. It will be shown that the rocks which constitute these three terranes, though so different in appearance, are genetically a unit, that they are eruptive and younger than the enclosing rocks, and that in their apparent diversity they may rightly be referred to as nickel-bearing rocks.

α. Exposures along the main line of the Canadian Pacific Railway.

This eruptive is well exposed in the railway-cutting between Murray and Rayside Stations. Its width here is about 4 miles. As the rock is freshest towards the centre of the area, it will be advisable to consider in detail specimens collected there; then to study in order the specimens collected between the fresh central or type-rock and the Murray Mines contact, and finally the specimens from the north-western half, beginning at the centre, and proceeding towards the north-western contact near Rayside Station.

The Type-rock.—About 1½ mile north-west of Murray Mines, near the point where the railway enters the township of Rayside, there are good exposures of a somewhat coarse-grained rock, which is greenish on the weathered surface, while the freshly-broken surfaces exposed in the railway-cuttings are nearly black, with a bluish tint. It is the diorite or greenstone of the prospectors, which the microscope shows to be norite. Hypersthene forms idiomorphic crystals, and seems to have been the first of the essential minerals to crystallize. Sections of this mineral when in the prismatic zone are stoutly rectangular, while sections parallel to the basis are octagonal and show indistinct prismatic cleavage. It is strongly pleochroic—rose-red, bluish-grey to nearly colourless. The crystals of hypersthene are generally bordered and veined with bastite, which often contains small grains of magnetite. In other cases the alteration has proceeded so far that one observes rectangular areas of bastite which contain only a few separated grains of hypersthene. Where the bastitic alteration-products border on plagioclase, a still further change occurs, in that bastitic fibres and magnetite-grains give place to a somewhat compact, strongly pleochroic, bluish-green hornblende. This latter change does not occur along borders between bastitic areas and biotite or magnetite. The felspar seems to participate, by contributing the alumina necessary for the formation of green hornblende.

Plagioclase is the most abundant mineral. The crystals are xenomorphic when in contact with hypersthene, which is thus seen to have crystallized earlier than the plagioclase. The broadly-twinned plagioclase-crystals are from two to three times as long as broad, and even in the thinnest sections are brownish, owing to the presence of innumerable dust-like inclusions, which are regarded as ilmenite, and are very characteristic of plagioclase in norites. Besides these brown inclusions, too small to admit of microscopic determination, there are colourless needle-like inclusions which form a network of three parallel systems. It is probable that these inclusions are parallel to the three edges formed by the pinacoidal faces. Measurements of extinction-angles lead to the conclusion that we are here dealing with bytownite.

Augite forms occasional, large, irregularly-bounded grains, which are non-pleochroic, and xenomorphic with respect to hypersthene and plagioclase. Inclusions parallel to OP give the appearance of basal cleavage when examined with a low power.

Besides the above-mentioned hornblende, which is of secondary origin, there is a small proportion of apparently primary nature. It never occurs alone in well-formed crystals, but mostly forms borders on crystals of hypersthene and on areas of bastite derived from these. This hornblende possesses well-developed cleavage, definite outline when bordering on felspar, is darker than the secondary hornblende, and is compact and not fibrous. Much might be said in favour of the secondary nature of this hornblende, where it could be regarded as the final product of the alteration represented by the change of hypersthene to a bastite-magnetite aggregate, this to bluish-green hornblende with no characteristic

outline or cleavage, and finally the hornblende in question with definite outline, strong pleochroism, and characteristic cleavage. Were this the case we should expect to find the largest amounts of this hornblende in rocks where alteration had advanced farthest. This, however, as will be seen later, is not the case, and hence it is preferable to regard this well-developed hornblende as primary, and as having formed borders on the pyroxene-crystals in the original unaltered norite. When so regarded, we find difficulty neither in explaining its presence as a border on perfectly fresh hypersthene-crystals, nor in its surrounding the bluish-green hornblende, which is undoubtedly of secondary nature.

Biotite is occasionally observed in well-developed scales, of whose primary nature there is no doubt. Secondary hornblende forms a very narrow border on biotite-scales when in contact with plagioclase.

Apatite, magnetite, and occasionally grains of iron sulphides are present, as is usually the case in such rocks. The very last mineral to crystallize was quartz, which is represented by a few irregular grains.

From this description it will be seen that the type-rock of the nickel-bearing eruptive exposed between Murray and Rayside Stations is a norite containing small quantities of biotite, hornblende, and augite. The slight alteration in no way obscures the original nature of the rock.

East of the Type-rock.—Eastward along the railway very little change is observed in the character of the greenstone for some distance. About $\frac{1}{4}$ mile east of the type-rock two intrusions of granite occur. The broader of these has a width of about 100 yards. The later age of this granite may be concluded, as it sends apophyses into the norite, and where in contact with the latter rock it has changed the pyroxenes to hornblende and biotite. Similar action may be observed on fragments of norite included in the granite. This intrusive granite will be fully described later. It is enough here to know that we have sufficient ground for regarding the norite as a continuous area.

About $\frac{1}{2}$ mile east of the type-rock the rock is macroscopically unchanged, except that it peels off in concentric layers when exposed to the weather, as is frequently the case with diabase, but not with norite. The microscope shows that it is more altered than the type-rock. Most of the hypersthene-crystals are so altered that generally only a few isolated grains can be detected in areas of secondary hornblende, whose areas are identical with those of the normal hypersthene-crystals. The secondary hornblende is the same as in the previous rock, except that there is relatively more pale bluish-green hornblende and less bastite.

A few needles of secondary pale-green hornblende occur in the plagioclase, as if the bastite-substance had been transported into the felspar, and had there produced the pale green hornblende, which in the type-rock occurred only where bastite bordered on felspar. The plagioclase constitutes two-thirds of the rock, and, except for the presence of hornblende-inclusions, does not differ from that of the type-rock.

Passing eastward, the rock becomes slightly finer-grained, but does not differ materially from the type-rock. About 200 yards from the smelting-works at Murray Mines, the rock when examined microscopically is seen to differ from the former specimens in two ways: there are differences on the one hand which are due to metamorphism, and these may be regarded as of secondary nature; and on the other hand there are differences of a primary nature, and these are to be explained as due to the differentiation of the original rock-magma. Neither crystals of hypersthene nor even preserved remnants of the mineral, such as were noticed in the previous rocks, can be observed, and we are able to prove its presence in the original rock only by reference to the areas of bastite and secondary hornblende. The more or less regularly rectangular areas have been derived from hypersthene, while quite irregular areas have been probably derived from augite. Primary hornblende is not so abundant as previously, while biotite, which appears to be of primary nature, is more abundant. Plagioclase is characterized by brown dust-like inclusions, and by small colourless crystals which are probably zoisite or epidote.

The plagioclase-crystals contain numerous particles of secondary green hornblende, which is at times so plentiful as to somewhat conceal the original felspar-boundaries. The same indistinctness is often observed in connexion with the secondary products resulting from hypersthene and augite. Bastite-substance seems to have been transported in solution from the original hypersthene-areas, and to have produced the secondary hornblende in the plagioclase by reacting upon it. Generally the solution followed cleavage-planes in the felspar, but frequently the cleavage-paths cannot be traced. This process, whereby secondary hornblende is formed by the action upon plagioclase of solutions carrying bastite-substance, and the deposition of the hornblende distant from the bastite-areas, may be referred to as the 'migration of hornblende,' and hornblende so formed may be called 'immigrated hornblende.'

Between the smelting-works and the Murray Mines ore-deposits the rock is finer-grained and more altered. The microscope shows that the secondary hornblende is nearly all of the bluish-green type, bastite having almost disappeared. The migration of hornblende has become much more general, so that the old boundaries of the bisilicates are very imperfectly preserved in the areas of their secondary products. It is also worthy of note that a few of the areas of secondary hornblende seem to have suffered a still further change, and to have given rise to dark brown, fine, scaly biotite. This seems to be the final product of the alteration which changes hypersthene successively to bastite-magnetite aggregate, pleochroic bluish-green hornblende, and finally scaly biotite. The production of biotite from secondary hornblende seems to have been much more frequent in the small individuals included in the felspar. The plagioclase swarms with epidote-crystals and shows very irregular

boundaries. Grains of chalcopyrite and pyrrhotite are very frequent.

In the railway-cutting quite close to the Murray Mines deposit, which is very near the south-eastern border of the Whitson Lake eruptive, the rock contains a large amount of pyrrhotite and chalcopyrite. It has been much more altered than the rocks already described. Hypersthene and augite have entirely disappeared and have been replaced by green hornblende, which does not appear to be confined to any definite areas. Primary plagioclase cannot be detected, but seems to have given place to small individuals which are broadly twinned and water-clear. A few scales of biotite, a little primary hornblende, numerous small irregular grains of quartz, and swarms of pyrrhotite- and chalcopyrite-grains, complete the list of constituents. The rock has been almost entirely recrystallized, and its original nature is somewhat concealed. In composition it corresponds at present to an uralitic diorite, and has doubtless been derived from a rock of the gabbro family. For convenience, these altered norites or gabbros will be referred to in the following pages as 'greenstones.'

Although the rocks collected along the railway near Murray Mines indicate a total disappearance of hypersthene and a large increase of secondary hornblende, yet there is good ground for regarding these rocks as having been derived from norite. The late Baron von Foullon described a rock which was blasted out when the foundations were being prepared for the smelting-works at Murray Mines, not more than 100 yards from the contact. This rock is described as containing strongly pleochroic semi-idiomorphic hypersthene-crystals, along with a smaller amount of diallage. He observes that these minerals are often bordered with hornblende. The rock on the dump at Murray Mines is generally fine-grained and too much altered to show hypersthene, but in the lower workings, 10 to 20 yards removed from the contact, the ore occurs in a rock of medium grain, which contains an abundance of fresh hypersthene. This rock shows a large amount of diallage-like augite and secondary hornblende, while plagioclase is not so abundant as usual, and has been partly recrystallized.

The contact with the granite on the south-eastern side of the eruptive is not very sharp. Granite is mingled with greenstone for 100 to 150 yards and often forms breccias with it. The breccias have a granitic grained matrix, and sharply angular greenstone-fragments which vary much in size. The granite is very fine-grained near the contact, and is certainly younger than the greenstone. It seems to have been intruded along the wall between the greenstone and the original clastic, which was in contact with the eruptive greenstone before the intrusion of the granite. A narrow band of this clastic may now be seen along the railway about $\frac{1}{2}$ mile east of the present contact of the Whitson Lake eruptive with the granite.

The nickeliferous pyrrhotite is intimately intermingled with the greenstone. Chalcopyrite is present in very much smaller quantity. The pyrrhotite often contains crystals of magnetite and biotite, which are consequently older than the pyrrhotite containing them. By examining some specimens one might conclude that the ores had crystallized before the silicates, while an examination of other specimens would lead to the opposite conclusion. The ores are, in fact, to be regarded as constituents of the rock, which at a few places along the border of the eruptive have been concentrated by differentiation, so that the ore-deposits are norite or greenstone, which is rich enough in chalcopyrite and nickeliferous pyrrhotite to be of commercial value. The quantity of the ores in the rock increases gradually towards the border, till it often constitutes three-fourths of the rock. Sometimes the ores and silicates are finely intermingled, while at other times comparatively pure masses of pyrrhotite and chalcopyrite are included in the silicate-groundmass. These masses of pure ore vary from a few lines to a foot in longest diameter. In other cases the ores appear to form the groundmass in which the silicates are included. Near the contact the grain of the ores is fine, and the proportion of chalcopyrite and pyrrhotite is often so large as to form deposits of economic importance, while farther from the contact the ore becomes coarser-grained and the quantity of silicates increases till it can no longer be worked at a profit. The nickel percentage of the pyrrhotite varies greatly, but may be safely stated as ranging from 3 to 7 for the deposits which have been worked on a large scale. There are, however, many deposits which contain less than 3 per cent. of nickel, but these are at present of no special value.

Vogt, in describing similar nickel-deposits in Norway, regards the pyrrhotite and chalcopyrite as rock-forming minerals, and believes that they took their present form at the time of the solidification of the rock containing them. He refers to the rock rich in pyrrhotite as 'pyrrhotite-norite,' and observes that the ores generally diminish with the distance from the contact. He regards the ores as the most basic rock-constituents, and considers that the pyrrhotite-norite is related to the greenstone in the same way as basic borders on granite-stocks are to the granite. Both, he maintains, have been formed by differentiation of once homogeneous magmas. My observations lead me to think that the same relations obtain in the case of the Sudbury chalcopyrite-pyrrhotite deposits.

Occasionally small masses of titaniferous magnetite are associated with the pyrrhotite. An analysis of such a mass from Murray Mines showed the presence of 18·34 per cent. of titanic acid. At other points along the border of the Whitson Lake eruptive similar masses of titaniferous magnetite occur. Portions of norite which are rich in titaniferous magnetite might well be so named as to indicate the presence of magnetite as an essential mineral. Similar peripheral separations of titaniferous magnetite are frequent in connexion with the gabbros of Minnesota, as Bayly has recently pointed out.

About 100 yards south of the office at Murray Mines a porphyritic facies of the greenstone occurs. The groundmass is fine-grained and weathers to a greenish colour. Crystals of black hornblende, varying in size from peas to 'marbles,' are richly scattered through it.

Rocks West of the Type-rock.—We shall now examine in turn the rocks collected along the railway between the type-rock and the north-western contact.

About $\frac{1}{4}$ mile north-west of the type-rock, there seems to be little change macroscopically. Small sapphire-blue grains of quartz are frequently observed in the dark rock. The microscope shows the complete alteration of hypersthene to bastite and green hornblende. The boundaries of the secondary products are fairly sharp, although there has been considerable migration of hornblende. Frequently the secondary hornblende is associated with scales of biotite, as if the latter had been produced from the former. Within the bounds of the old hypersthene-areas the hornblende extinguishes in two portions, and presents in some cases, between crossed nicols, the appearance of polysynthetic twinning on the orthopinacoid. There are occasional irregular areas of secondary hornblende, as if derived from augite. Primary hornblende and biotite are present in about the same proportions as in the type-specimen. Micropegmatite forms a few small areas, and seems to have been one of the last constituents to crystallize.

One mile east of Rayside Station the rock becomes quite coarse and gabbro-like. The dark minerals constitute only a third of the rock. Microscopically it differs from the last specimen in the total disappearance of the bastite stage of secondary hornblende, an increase in fine scaly biotite in association with immigrated hornblende, and an abundance of epidote-crystals in the plagioclases. The original rock was of a somewhat more acid character than those previously examined, as indicated by an increase in the quantity of quartz and micropegmatite. There are a few grains of a mineral which is strongly pleochroic—purple, rose, colourless—and which is generally associated with the bisilicates. It is probably orthite.

Westward the rock takes on gradually the appearance of a granite. The weathered surface is white to pink instead of green, while an indistinct parallelism is sometimes noticeable. Fine scaly biotite is more prominent, while the large, bright, black cleavage-surfaces of hypersthene, biotite, and hornblende are seldom observed.

A specimen collected about $\frac{1}{4}$ mile west of Rayside Station represents the north-western border of the area. The weathered surface is pale pink. Parallelism in the constituents is very apparent, so that the structure is coarsely gneissoid. The texture is finer than in the central portion of the eruptive. The microscope shows that fine scaly biotite is the only bisilicate present, that orthoclase is much more abundant than plagioclase, and that quartz in small grains makes up about half the rock. This granitic rock has been subjected to considerable pressure, as indicated by the undulatory extinction of the quartz-grains and the bending and breaking of the plagioclase-crystals.

Quite at the contact, in a hill $\frac{1}{2}$ mile north-west of Rayside

Station, the slate has been so altered by the eruptive as to lose its schistosity and to resemble the 'hornfels' so commonly produced by granite when in contact with slate. This rock is shown by the microscope to be composed of fine scales of biotite and muscovite and grains of quartz. The quartz-grains are bounded by polyhedral outlines, so as to produce the 'pavement'-structure which is so characteristic for contact-products. Roundish mica-scales are frequently included in the quartz-grains. These microscopic structures confirm the contact nature of the rock. Calcite-grains are so common that the rock-powder effervesces briskly with cold hydrochloric acid.

There are numerous inclusions of quartzose fragments in the eruptive near the junction. The presence of these quartzite-inclusions in the eruptive indicates that it has broken through quartzitic strata, which consequently underlie the slates at present observed in contact with the granite.

β. *Exposures north of Blezard Mine.*

The south-eastern contact is only a short distance south of Blezard Mine. The rocks are well exposed along the road north of the mine, while excellent opportunity is afforded for geological examination by the rocky shores and islands of Whitson Lake. The rocks of this cross-section of the Whitson Lake eruptive are quite similar to those studied in the previous one along the main line of the Canadian Pacific Railway.

The rock a short distance north of the mine is almost identical with the type-rock of the last series. It is dark, and of medium texture. The freshly-broken surface shows a few scales of biotite.

Specimens collected 200 yards south-west of the mine along the railway show that the rock has undergone considerable alteration. The original bisilicates and plagioclase have been replaced by secondary hornblende and irregular water-clear grains of plagioclase, which are generally accompanied by small grains of quartz.

Northward from Blezard Mine the rocks show an increase in acidity and alteration. By canoe one may visit the shores and islands of Whitson Lake, where further changes are observed. On an island about $\frac{1}{2}$ mile south of the narrows the rock begins to show a granitic appearance, the quantity of quartz is much larger, brown scaly biotite and a little secondary hornblende represent the bisilicates, while untwinned orthoclase-felspar is present in about equal quantity with the narrowly-twinned plagioclase.

Areas of secondary hornblende generally extinguish more or less distinctly in two portions, but in sections of the above rock this manner of extinction is very plain. Moreover, in some cases hornblende twinned polysynthetically on $\infty \mathrm{P} \infty$ is connected with these areas, and one part of the hornblende-mosaic extinguishes with one series of twinning-lamellæ, while the other part of the mosaic extinguishes with the alternate series of twinning-lamellæ. This proves that the hornblende of the mosaic is oriented in the position for twinning on $\infty \mathrm{P} \infty$. It differs, however, from the ordinary twinning, in that there is complete interpenetration of the hornblende-individuals, which in the ordinary twinning are separated by straight lines, as is the case with plagioclase when twinned polysynthetically. It has been long remarked that areas of secondary hornblende extinguish in two portions, but the exact orientation of the one portion with reference to the other has not been previously determined.

Specimens from an island near the narrows of Whitson Lake show distinct parallelism, and appear to be gneissoid granite. The scaly biotite which occurred sparingly in the previous specimens is here a prominent constituent, and forms continuous films of small individuals, which give to the rock its parallel structure. Orthoclase is much more prominent than plagioclase, while micropegmatite constitutes nearly half the rock. It is interesting to note that the felspar present in the micropegmatite is well-twinned plagioclase.

Farther north the islands and shores present the same rock as that just described, except that scaly biotite, quartz, and orthoclase are almost the sole constituents. Micropegmatite nearly disappears in the northernmost specimens. Sometimes the rock contains numerous grains of calcite, which is well twinned and water-clear. This mineral is certainly not a decomposition-product of the granite, which is quite fresh. It may be a primary constituent, or more probably an infiltration into the small cavities of the originally somewhat porous rock. Similar calcite-granites have been reported by Hawes from New Hampshire, and by Törnebohm from Guömålo in Sweden.

The north-western contact occurs at the extreme north of the lake, near the mouth of a small creek. The rock to the north-west is the silicified breccia previously described.

This cross-section of the Whitson Lake eruptive shows that it extends from a short distance south of Blezard Mine to the northern end of the lake, a distance of $3\frac{1}{2}$ miles, and that there is a gradual increase in acidity towards the north.

γ. *Exposures along the line between Lots 8 and 9 in the Township of Snider.*

A two days' trip was made through the woods along the line between lots 8 and 9 in the township of Snider, in order to study further and map the Whitson Lake eruptive. It was found that on the southern shore of the lake the rocks exposed were gneissoid granites similar to those seen near the narrows of Whitson Lake. The contact occurs about $\frac{1}{2}$ mile north of the lake. Passing southward towards Meat Bird Lake, the granite gradually gave place to the normal greenstone. The southern contact was found to be near the boundary-line between concessions II. and III. Its width is therefore about 4 miles.

Thus it is seen that this section of the Whitson Lake eruptive is quite similar to the two sections already described.

While engaged as an assistant on the Canadian Geological Survey in 1890, and exploring south of White Water Lake with a view to determining the boundaries of the eruptive, I first observed that there was not a sharp boundary between the greenstone and the granite lying north-west of it, since there appeared to be everywhere a gradual transition from the one to the other.

In the previous pages it has been shown that such transitions occur along all the cross-sections of the Whitson Lake eruptive. The variations in chemical composition of these rocks are illustrated in the following series of analyses of specimens collected along the Blezard Mine crossing. The specimens range from south to north, from I to V. I am indebted for analysis IV to Mr. C. B. Fox, M.A., chemist of the Iron and Steel Company, of Hamilton, Ontario:—

	I.	II.	III.	IV.	V.
	%	%	%	%	%
SiO_2	49·90	51·52	64·85	69·27	67·76
TiO_2	1·47	1·39	......	0·78	0·46
P_2O_5	0·17	0·10	0·24	0·06	0·19
Al_2C_3	16·32	19·77	11·44	12·56	14·00
Fe_2O_3	......	·47	2·94	2·89	......
FeO	13·54	6·77	6·02	4·51	5·18
CaO	6·58	8·16	3·49	1·44	4·28
MgO	6·22	6·49	1·60	0·91	1·00
MnO	trace	trace	trace	trace	trace
K_2O	2·25	0·70	3·02	3·05	1·19
Na_2O	1·82	2·66	3·92	3·12	5·22
H_2O	0·76	1·68	0·78	0·76	1·01
Total	99·03	99·71	98·30	99·35	100·29
Specific gravity =	3·026	2·832	2·788	2·724	2·709

Several of the most important nickel-deposits occur along the south-eastern border of the Whitson Lake eruptive; among others the Blezard, Murray, Little Stobie, and Lady McDonald mines.

(iii) The Windy Lake Eruptive.

This eruptive is situated about 25 miles north-west of Sudbury, and is known to extend from the township of Lavack south-west to the township of Trill, a distance of 20 miles, though its total length is probably much greater. Exceptional opportunity is afforded for the examination of this eruptive by the cuttings of the Canadian Pacific Railway near Windy Lake, where the rock extends over a width of nearly 4 miles. Onaping Station is situated near the south-eastern border of the area.

About 3½ miles west of Onaping Station the railway passes through a ridge of greyish to pinkish, heavily-bedded gneiss, which was described at the beginning of this paper (p. 42). On travelling eastward a few hundred feet along the low margins of Windy Lake no rocks are observed, but a little farther east there are exposures of a medium-grained rock, in which the unaided eye distinguishes a black mineral occurring as separate grains, and a much more

abundant white mineral forming the groundmass for the dark mineral. Though a norite, this rock differs in appearance from the Whitson Lake eruptive in being coarser-grained and of a much lighter colour.

The microscope shows that here the hypersthene, though often quite fresh, is more frequently changed partly or even entirely to bastite or secondary hornblende. The plagioclase-crystals are quite free from the dusty-brown inclusions observed in the plagioclase of the Whitson Lake norite. This difference is largely responsible for the comparatively light colour of the Windy Lake norite as contrasted with the dark colour of the Whitson Lake norite.

A specimen collected ½ mile east differs from the last in being slightly more altered and of somewhat more acid character. Some crystals of plagioclase exhibit in an unusual degree zonal structure and wandering extinction. In some cases there is a difference of 38° between the extinction of the central and marginal portions of the same individual. Such plagioclase-crystals generally border on small areas of quartz and micropegmatite, and appear to have continued their growth till all the constituents except the quartz and micropegmatite had crystallized. The central portion is therefore composed of one of the most basic plagioclases, while the marginal portion represents one of the most acid of the series.

Eastward the rock becomes coarser in grain, and the greyish norite gives place to what might be taken macroscopically for a hornblende-syenite. A specimen collected 2¼ miles west of Onaping Station, when examined microscopically, shows that secondary hornblende is the only bisilicate present. Micropegmatite and quartz are more abundant: the felspar of the micropegmatite is well-twinned plagioclase. There are a few grains of a yellowish pleochroic mineral, which has strong polarization-colours and a high index of refraction. As this mineral becomes much more abundant near Onaping Station, it will be more fully dealt with later: it seems to alter to radiating aggregates of pale lemon-yellow hornblende.

Towards Onaping Station there is a marked increase in the quantity of micropegmatite, which forms about half the rock. Well-defined felspar-crystals form the centres for radiating micropegmatite areas. Taking into consideration the prominent part played by micropegmatite and the porphyritic nature of the rock, it may be called a 'hornblende-porphyry with a micropegmatitic groundmass.'

There is, moreover, another important constituent. This occurs commonly in groups of irregular grains, and is distinctly pleochroic—lemon, yellowish-green, and colourless. The index of refraction is high, and the surface appears to be quite rough when seen under the microscope. The double refraction is high, so that it polarizes in orange-green and red tints when quartz of the same thickness polarizes in grey. It is always associated with the radiating aggregates of secondary hornblende above mentioned. This mineral appears to have occupied a prominent place in the original rock, where it largely replaced the bisilicates. Having crystallized later than the quartz, it presents very seldom idiomorphic forms. The same mineral is a very frequent accessory in the Norwegian zircon-syenites, though the secondary products are not so well developed there as in the Onaping rocks. This mineral has been identified in the zircon-syenites as wöhlerite, and it is possible that the associates of wöhlerite may be found in the Sudbury nickel-bearing rocks. A mechanical or chemical separation of this mineral was impossible.

The reddish granite at Onaping Station is composed of micro-pegmatite, orthoclase with a little free quartz, and about equal quantities of wöhlerite and secondary hornblende, which was probably derived from the former. Orthoclase has replaced plagioclase in the micropegmatite, which constitutes about two-thirds of the rock, and has attained a high degree of perfection. Wöhlerite is present as grains, which at times deserve the name of crystals, and may be seen to be optically biaxial, with a very large optic angle. The secondary hornblende derived from it contains numerous delicate feathery crystals of biotite, which are also probably of secondary nature.

South-eastward from Onaping, near the contact, the granite becomes fine-grained and darker in colour, while the microscope shows a slight increase in plagioclase and iron ores, and a decrease in free quartz.

In this eruptive, as in the one previously described, micropegmatite is characteristic for the granitic rocks connected with basic noritic borders. Harker has observed the same occurrence in his studies of the Carrock Fell gabbro in England. Elsewhere micropegmatitic rocks are generally muscovite-bearing, but in the Sudbury eruptives muscovite is very seldom found. A wider examination might show that micropegmatite is characteristic for all rocks which are midway between the more acid and the more basic portion of differentiated eruptives.

Some of the most important deposits of nickeliferous pyrrhotite discovered in the Sudbury district are situated along the north-western border of the Windy Lake eruptive. We have here to deal with an eruptive whose length is unknown, and whose width is nearly 4 miles. The gradual transition, from typical pyrrhotite-norite on the one hand to hornblende-granite on the other, shows that in most respects it is identical with the Whitson Lake eruptive. These eruptive areas, which are bordered locally with norite and pyrrhotite-norite, cannot properly be spoken of as basic eruptives, since the average acidity for the whole of the eruptives is at least 62 per cent. of silica. In this respect the Sudbury nickel-bearing eruptives differ from those of Norway as described by Vogt.

Bell's map shows a greenstone area extending from Lake Sagi-tchi-wai-a-ga-mog south-westward into the township of Morgan. This area is in all probability only a basic border of the Windy Lake eruptive. In this case the length of the eruptive is at least 25 miles, while further investigation may show that it is even longer.

Specific-gravity determinations, of a series of specimens collected along the railway where it crosses the Windy Lake eruptive, show a decrease from each border towards the centre, where the lightest and most acid rocks occur. The following numbers are averages of pairs of specimens, so that the error inherent in determinations made on small fragments is more or less eliminated:—

Eastern contact	2·714
" "	2·746
" "	2·690
Onaping Station	2·722
" "	2·793
Western contact	2·851

(iv) The Travers Mine Eruptive.

This nickel-bearing area is situated in the townships of Drury and Denison, about 25 miles south-west of Sudbury. It is most easily reached from Worthington Station on the 'Soo' branch of the Canadian Pacific Railway. Bell maps it as being nearly a mile wide and 6 miles long.

The rock on the dump at Travers Mine is fine-grained, dark greenish-grey, and in some cases exhibits a schistose structure. The microscope shows that it is composed of fine granular felspar, uralitic hornblende, a very little hornblende-epidote, and iron ores. The schistosity is often very distinct, and is caused by the bisilicates forming lengthened, irregularly-pointed, elliptical areas, which alternate with granular felspar-epidote masses, that constitute two-thirds of the rock.

Farther south the rock is composed of the same minerals, but is often much coarser. Locally there are small patches which are nearly pure felspar-epidote aggregate, while in other places there are dark patches which contain very little felspar-epidote aggregate. A mile and a quarter south of the mine the rock becomes very much coarser.

The rocks of this area resemble the well-known flaser-gabbros of Rosswein, Saxony, and differ widely from the rocks of the two areas already studied. At present it is composed of saussurite flaser-gabbro, especially rich in saussurite. The flaser-structure has probably been caused by great pressure, which hastened the uralitization and saussuritization of the components, and may have produced the crushed granite north of the Travers Mine. I have not determined the relation of the gabbro to the granite north of the mine, but I think that the two are genetically distinct.

V. Other Nickeliferous Areas.

The Stobie Mine is connected with a long narrow area of somewhat schistose greenstone, which is only a few yards wide where crossed by the Blezard branch of the Canadian Pacific Railway. The specimens collected indicate an approach to amphibolite. The Huronian rocks have been metamorphosed by this now highly-altered greenstone; garnet and biotite are the chief new minerals, while the whole rock has been rendered quite crystalline.

Copper Cliff Mine is also situated on a very narrow eruptive stock. The greenstone is so much altered that its original nature is quite concealed. The microscope shows that uralite, a little secondary hornblende, plagioclase, free quartz, and a little micropegmatite are the chief constituents. This rock is thus seen to be much more acid than that examined at any of the other nickel mines.

Worthington Mine is connected with an eruptive which is not more than 50 yards wide where the 'Soo' branch of the Canadian Pacific Railway crosses it at Worthington Station. The rock is very schistose, and greenish-grey in colour. Some of the fresher specimens might be called actinolite-schist, while others are largely changed to a fine aggregate of talc, which contains only a few slender actinolite-crystals. Pyrrhotite-grains are richly scattered through the rock.

There are a few areas of hornblende-schist in the Sudbury district, but it is difficult to determine whether they should be regarded as crystalline schists and proper members of the Huronian, or as altered greenstones. One of the largest and most accessible of these areas is cut by the main line of the Canadian Pacific Railway, about 3 miles west of Sudbury. The rock is rather compact, distinctly schistose, and nearly black in colour. The microscope shows that it is composed of long, slender crystals of bluish-green hornblende, a smaller quantity of quartz and water-clear grains of felspar.

Narrowly elliptical quartz-grains form parallel chains of inclusions in the hornblende-crystals. These inclusions occupy a definite plane, which, from the following observations, appears to be the positive orthodome $+\bar{P}\infty$. (The face usually marked *p* is here taken to be the basis *o*P):—

(i) In sections of hornblende-individuals the inclusion-chains are at right angles to the cleavage—hence they lie in a plane of the orthodiagonal zone.

(ii) The maximum extinction for sections parallel to $\infty \mathfrak{P} \infty$ is 13° 55′. Such sections show that the chains of inclusions form an angle of 75° with the cleavage, and an angle of 89° with the axis of elasticity  .

(iii) Sections with smaller angles of extinction give larger angles between the cleavage and the inclusion-chains.

Similar disjointing of blade-like crystals by pressure is observed in many minerals, particularly in the piedmontite of Japanese piedmontite-schists. Parting of hornblende-crystals along $+\bar{P}\infty$ has been observed by Cross in actinolite-schists from Britanny, and also less perfectly in green schists from Zermatt in Switzerland.

The same amphibolite-area may be examined about ½ mile north of Copper Cliff Mine. The nickel-bearing rocks at Stobie Mine resemble these amphibolites, and it is possible that they are all connected.

It is worthy of note that most of the narrow areas of nickeliferous rocks have been acted upon by dynamic metamorphism with comparative ease, and as a result the original unaltered rock is seldom found in the smaller eruptives. The original rock was probably a massive norite or gabbro, which was changed into schistose hornblende-rock. This is seen in the rocks of the Stobie, Travers, and Worthington eruptives. On the other hand, large eruptives such as the two first described have retained their massive structure and to a large extent their pyroxene content.

As compared with the Norwegian nickeliferous rocks, the Sudbury rocks are decidedly more acid, for olivine, which is a frequent constituent of the former, has never been detected in any of the Sudbury nickeliferous rocks.

VI. The Younger Granites.

We must now refer briefly to a class of granites which are younger than the nickeliferous rocks, and may be conveniently spoken of as 'Younger Granites.' The best exposures of these rocks occur on the main line of the Canadian Pacific Railway, about 2 miles west of Murray Mines. The nickel-bearing rocks are there cut by two separate eruptions of fine-grained, pinkish biotite-granite, which sends off apophyses into the surrounding greenstone. The wider of these intrusions is about 100 yards broad, while the smaller is less than 60 yards. The microscope shows that quartz, orthoclase, plagioclase, and biotite are the chief constituents.

Where the rock comes into contact with the norite, the hypersthene, hornblende, and augite of the latter are changed to fine scaly biotite, while the well-formed plagioclase is replaced by an aggregate of granular plagioclase, epidote, and quartz.

Another exposure of this rock occurs immediately south-east of Murray Mines, where it cuts through the nickeliferous greenstone, sometimes forming apparent inliers in the same. In other places breccias are formed by the inclusion of angular fragments of greenstone in a groundmass of fine-grained pinkish granite.

It appears as if there had been an intrusion of this granite along the contact between the nickel-bearing eruptives and the Huronian rocks south-east of them. The width of this granitic intrusion is over ½ mile. It contains numerous inliers of greenstone. A narrow strip of mica-schist 11 yards wide is exposed along the railway on the south-eastern border of the granite. The schist dips at very high angles, and doubtless represents the rock which was originally in contact with the nickel-bearing eruptive. Similar exposures of fine-grained granite are observed immediately south of Blezard Mine.

North of Copper Cliff Mine there is a large area of coarse gneissoid granite, which the late Baron von Foullon considered to be Laurentian. It is essentially the same rock as that exposed east of Murray Mines, except that the latter has been so crushed as to present a much finer grain.

VII. Olivine-Diabase Dykes.

These dykes are the youngest of the Sudbury rocks, and are characterized by north-westerly direction with only very slight variations. All the other rocks of the district are intersected by them. The extensive area over which these dykes occur, taken in connexion with their general parallelism, points to a period of great dynamical action. The force that produced the cracks through which the diabase-magma ascended had doubtless a part in the production of amphibolites and flaser-gabbros from massive pyroxene-rocks, in the metamorphism of the norites, and in the crushing of the Younger Granites and granitic borders of the nickel-bearing areas. As the dykes intersect all the other rocks, we may conclude their post-Huronian age, though it is impossible to say whether they were formed in early Palæozoic or in comparatively recent times.

One of the best representatives of this dyke-system is well exposed quite near the town of Sudbury, and can be followed for 7 miles. The easternmost exposure is on the southern shore of Ramsay Lake, near the north-western point of the peninsula which nearly divides the lake. It appears again on the north-western shore near the landing, and the dyke may be followed by frequent exposures past the town of Sudbury. All the exposures of diabase along the railway between Sudbury and Rayside Stations are portions of the same dyke.

Another dyke of this system crosses the railway 1 mile east of Worthington Station, and a third about $\frac{1}{4}$ mile east of the station. A very large dyke is well exposed on the railway near Nairn Station. Many others might be mentioned, some of which are said to have other directions, but all those examined by the writer have a general north-westerly direction. In width they vary from a few feet to 50 yards.

Plagioclase is the chief constituent. It is generally quite fresh, but is occasionally somewhat clouded. Idiomorphic much-twinned crystals are characteristic. From measurements of the angles of extinction the felspar seems to be labradorite. The twinning is commonly of the albite law, but a combination of the albite and pericline laws is frequent. In a section from the large dyke near Murray Mines twinning was observed combining the albite, pericline, and Baveno laws. Twinning of plagioclase according to the Baveno law was first mentioned by Weiss, and more fully described by Brezina. The combination of this rare twinning law with the albite and pericline laws as exhibited in the diabase from near Murray Mines is very interesting, and probably has never been previously observed. Plagioclase being by far the earliest to crystallize, the ophitic structure is beautifully developed.

The quantity of monoclinic pyroxene varies. In the exposure near Murray Mines it forms about a quarter of the rock, while at other points on this dyke, as also in the dykes near Worthington Station, it does not constitute more than an eighth of the rock. Where there is most pyroxene there is least olivine, and *vice versâ*,

so that the total quantity of pyroxene and olivine is nearly constant. The olivine forms more or less rounded, pale greenish-yellow grains, which are younger than the plagioclase, but older than the augite. Sometimes the olivine has given rise to small quantities of serpentine and swarms of minute grains of magnetite. The pyroxene shows no definite outline, and very seldom imperfect cleavage: it is reddish-brown to violet in colour, and distinctly pleochroic. The usual accessory minerals are present, and the rock is remarkably fresh.

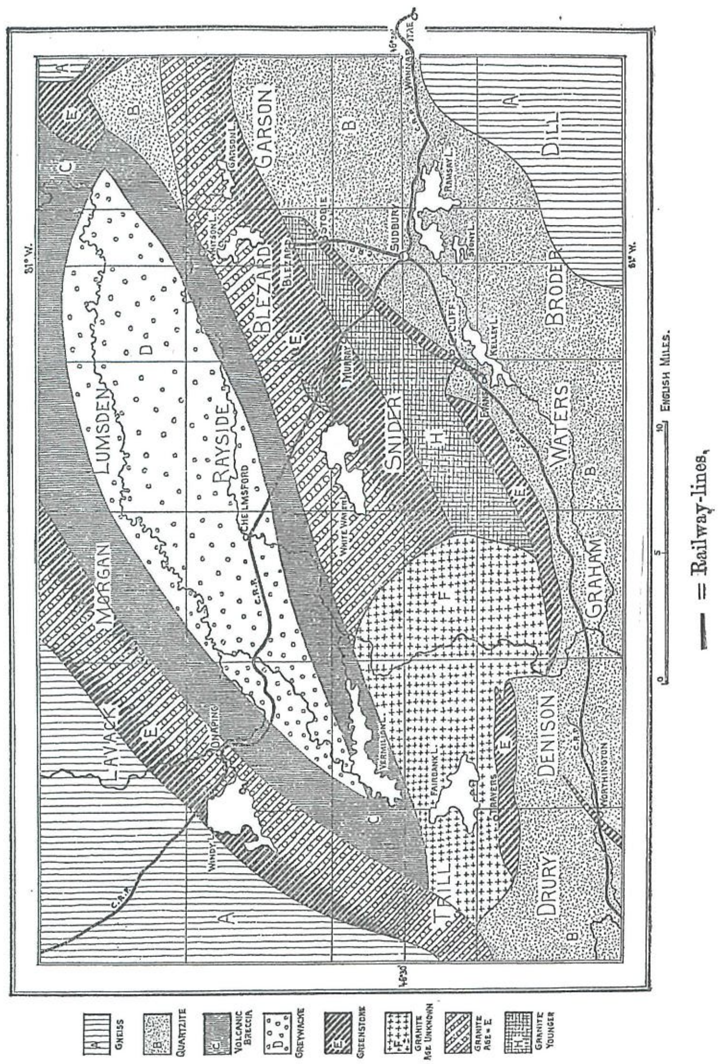
One point characteristic of these dykes is the ease with which they are acted upon by hydrochemical agencies. Near the village of Murray Mines the Government road passes for some distance between high walls of granite, which have become prominent by the weathering-out of the diabase. The nickel-bearing greenstones resist the action of atmospheric agencies much better, and are generally greenish on the weathered surface. In this respect they stand in contrast to the rocks under discussion, which become quite rusty on exposure. Spheroidal weathering is characteristic.

One of the exposures on the railway immediately east of Worthington Station contains porphyritic crystals of plagioclase from 1 to 2 inches long. This porphyritic phase is confined to within 2 yards of the contact. No glassy borders were observed in connexion with these dykes, but this may be due to the ease with which the rock decays. The large dyke, where exposed on Ramsay Lake, exhibits a gradual change in texture from very fine at the borders to quite coarse in the central portions. A microscopic examination of the marginal and central portions shows that they are mineralogically identical, and that there has been no differentiation. This is confirmed by specific-gravity determinations of a series of specimens representing a cross-section of the dyke where its width is about 40 yards.

A quantitative analysis of a specimen from the big dyke near Murray Mines gave the following result:—

	%
SiO_2	47·22
Al_2O_3	16·52
Fe_2O_3	3·32
FeO	12·40
MnO	0·04
CaO	9·61
MgO	3·33
K_2O	0·67
Na_2O	3·40
TiO_2	3·62
P_2O_5	0·33
BaO	0·01
CuO	trace
NiO	0·0275
CoO	0·0055
Loss by ignition	0·30
Total	100·803
Specific gravity	3·01

Geological Sketch-map of the Sudbury District.



The proportions of ferrous oxide and titanic acid are unusually large. The latter doubtless occurs partly in the magnetite and ilmenite and partly in the augite, giving this last its peculiar violet colour. It has long been known that nickel is a frequent constituent of the heavy ferro-magnesian minerals, especially of olivine and pyroxene, and it is probable that the heavy metals contained in the diabase are constituents of these silicates. Whether the nickel, cobalt, and copper were primarily constituents of the diabase-magma or not would be difficult to say, as they may have been derived from the nickel-bearing greenstones which are intersected by these dykes. Fragments of the nickel-bearing rocks may have been absorbed by the diabase-magma. I am, however, inclined to regard the nickel content of the diabase as a constituent of the original diabase-magma. No nickel-deposits have been found associated with these dyke-rocks.

Had the nickeliferous diabase solidified more slowly and been richer in sulphur, the nickel would probably have separated as iron-nickel sulphides along the border, as it did in the case of the nickel-bearing greenstones, where these differentiations of pyrrhotite-norite now constitute the most extensive nickel-deposits in the world.

The map which accompanies this paper is founded on that issued by the Canadian Geological Survey. It differs, however, in two ways from the Government map. Firstly, I have omitted much of the detail both in topography and geology, and have reproduced only such features as are necessary to illustrate the present paper. The second difference is wholly geological, and consists in such changes as my own explorations showed to be necessary. These changes are principally connected with the Whitson Lake and Windy Lake eruptives, and with the Younger Granites.

The investigations reported in this paper were carried on under the direction of Herr Geheimrath Professor Zirkel. It affords me great pleasure to acknowledge my indebtedness to him for his friendly advice and encouragement.

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DISCUSSION.

The PRESIDENT said that all additional information in regard to the Huronian rocks, which resemble so closely the volcanic rocks of pre-Cambrian age in Wales, was most useful at the present time. The Author's paper, therefore, was one in which British geologists would necessarily be much interested.

Prof. BONNEY said that, so far as he had seen the district, he doubted whether the ore was the result of differentiation. He believed that it was more likely to have been introduced afterwards, as is commonly the case with mineral ores. He thought also that the Author was pushing this idea of differentiation too far in regard to the rocks of the country. So far as he knew, there was a number of separate bosses of various kinds of rocks.

Mr. TEALL said that hyperites were associated with the Loch Dee granite in the South of Scotland, and that pyrrhotite occurred in some of the altered forms of these rocks. This pyrrhotite, however, in the specimen he had examined was certainly not nickeliferous to anything like the same extent as the Swedish and Canadian varieties. The association of nickeliferous pyrrhotite with hyperites and norites was now known from a very large number of localities in various parts of the world, and the differentiation-hypothesis had been advanced by Vogt to explain the association

The paper was based on a large amount of field as well as laboratory work. Its main object was not to establish a theory, but to describe facts.

Gen. M^cMAHON referred to the theoretical portion of the paper, and commented on the difficulty of understanding how the law of gravitation could be appealed to as the explanation of the basic portions of slowly-cooling magmas concentrating in the centres of eruptive masses, combined with the formation of acid rocks on both margins.

The Rev. J. F. BLAKE also spoke.