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THE SUDBURY NICKEL INTRUSIVE

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THE SUDBURY NICKEL-BEARING INTRUSIVE

The Sudbury region, which produces over eighty per cent. of the world's nickel, has been of interest to geologists for many years because of the probable segregation of its ore bodies from a sheet of intrusive rock. The early prospectors forty years ago found a connection between the nickel ore and "diorite", and in 1889 Robert Bell was sent by the Geological Survey of Canada to work out the geology of the region and found that there were two bands or ranges of nickel-bearing rock considered to be diorite, a northern range and a southern range.[1] In 1897 a great advance was made by T. L. Walker, who proved that the rock associated with the ore, now known to be norite, passes into an acid phase, micropegmatite, and that the two bands are arranged in opposite ways, the acid phase of the northern range being on the southeast side and that of the southern range on the northwest.[2]

Later Barlow worked over parts of the mining region for the Geological Survey; and in 1902 Coleman began the mapping of the district for the Bureau of Mines of Ontario, with Culbert and Moore as able assistants. In 1904 Barlow published an excellent report on the geology of the region with maps of the more important mines.[3]

In 1905 Coleman, after three summers' work, completed a map of the norite-micropegmatite and the adjoining rocks and showed that instead of two separate ranges there was a continuous sheet of intrusive rock forming a boat-shaped basin with a broad stern to the northeast and a blunt bow toward the southwest. The basin proved to be 37 miles long and 17 miles wide, and the sheet was found to dip

[1] Bell, R., Geol. Sur. Can., Vol. 5, Pt. F.
[2] Walker, T. L., Quart. Jour. Geol. Soc., 53, p. 40.
[3] Barlow, A. E., Geol. Sur. Can., Vol. XIV, 1901, Part H.

inward on all sides, though this is obscured by faulting at a few points on the south. Its average thickness was placed at about a mile and a quarter, though it varies a good deal, being much wider, and probably thicker, on the southeast side.

It was found that the broadest parts of the intrusive sheet were associated with much more ore than the narrow parts, so that it was desirable to map the inner (micropegmatite) edge, as well as the outer or norite edge, with which the ore deposits were connected.[1]

The interior of the basin is filled with sedimentary rocks, the Trout Lake conglomerate, the Onaping tuff, the Onwatin slate and the Chelmsford sandstone in upward succession. These are probably of Animikie age and have a total thickness of nine or ten thousand feet. They dip inward at about 30° and conform to the shape of the intrusive basin. On the other hand the rocks beneath the norite are often steeply tilted and mixed with basic and acid eruptives. They are much more ancient and include granite-gneiss on the northwest, and quartzite, graywacke, hornblende schist, etc., of the Sudbury series on the southeast.

Both the norite and the micropegmatite phases of the intrusive have in places penetrated the adjoining rocks, showing that the sheet is of later age; and it is apparent that the molten mass coming up from below found a zone of weakness where the Animikie sediments rested on the upturned older rocks, and spread out beneath them forming the present synclinal basin.

Where the nickel-bearing norite has been weathered away from the basement, one often finds a crush conglomerate of pebbles and boulders cemented by norite or ore still remaining in hollows of the ancient floor. This is well displayed at the Sultana and Whistle mines at the two ends of the basin, and gives a vivid idea of the forces at work when the intrusive spread out under the load of overlying Animikie beds.

In the summer of 1911 Coleman went over the ground

[1]Coleman, A. P., The Sudbury Nickel Field, Bur. Mines, Ont., Vol. XIV, 1905, Part III.

again to prepare a new edition of the map of 1904 for a report on the Nickel Industry, published by the Mines Branch of the Department of Mines in 1913.[1] The changes required were unimportant; and after six summers' field work, during which every prospect and ore deposit was studied and the margin of the intrusive was mapped in detail, certain conclusions were reached which may be outlined here.

The characteristic relations of the intrusive sheet to the other rocks are well seen in sections from the interior of the basin to one of the ore bodies of the southern margin, such as the Creighton mine. Rough hills are encountered near the outer edge of the tuff and in the basal conglomerate, where the sediments have been metamorphosed and hardened by emanations from the micropegmatite; and in places vaguely edged projections of acid rock penetrate the conglomerate, and its matrix often resembles the micropegmatite so that the boundary between the two rocks is uncertain within a hundred yards.

Where the acid edge of the intrusive has not been squeezed into schist, it usually has the appearance of a rather coarse grained reddish syenite, and this phase continues for a couple of miles, when the colour gradually becomes gray and at length the rock may be called norite. There is no great variation in the appearance of the norite for a mile or two, except the presence of rusty spots due to the weathering of blebs of ore as the basic edge is approached. These increase until broad bands of rock are brown with gossan, and finally just before the mine is reached, everything is hidden under a thick mass of reddish-brown iron ore.

The relations of ore to rock were beautifully shown at the Creighton mine in the early days when it was worked as an open pit. There was no distinct boundary to be seen between them, but mining was stopped when the mixture carried less than 2.5 or 3 per cent. of nickel and copper, since a lower grade was not profitable. The pyrrhotite-norite exposed in the wall of the open pit was often perfectly fresh, as shown by thin sections studied with the microscope, and

[1]Coleman, A. P., The Nickel Industry, Can. Dept. of Mines, 1913.

every gradation could be found between nearly pure sulphides including a few of the rock minerals, and norite more or less spotted with ore merging into the ordinary rock some hundreds of yards away.

At the other side of the open pit the ore usually had a sharp boundary against the foot wall of granite or greenstone, though it sometimes pushed into fissures or enclosed unweathered fragments of the rocks beneath. The two sides of the ore body were in absolute contrast.

During the work of mapping the margin of the norite, it was found that outward bends showed gossan, and if large, enclosed ore bodies; but inward bends showed little or no gossan and never supplied ore; and it soon became evident that the width of the intrusive controlled the amount of ore in these outward bays. Along the narrowest part of the intrusive on the north side there was no ore and the prospectors had not taken up claims; while the widest parts on both sides furnished great deposits.

As the mapping progressed, new terms became necessary for the ore bodies, which differed greatly from the vein deposits of most other mining regions; and unsymmetrical sheets of ore at the edge of the norite, as at Creighton, were called marginal mines; while others which pushed out into the country rock as more or less columnar deposits were called offsets, the typical example being the once famous Copper Cliff mine. The offset deposits were enclosed in the country rock, but there was always more or less norite with the ore, showing its derivation from the intrusive, and except in the case of the Frood, which is a parallel offset, there was always a bay of norite projecting toward them with a line of faulting providing channels by which they were reached.

The rocks enclosing offset deposits were generally found to be somewhat metamorphosed and there were often developments of vein quartz or carbonates due to hot solutions coming from the norite, unlike the typical marginal mines, which are almost without evidences of hydrothermal action.

Both kinds of ore deposit were associated with pyrrhotite-norite, usually more or less weathered in offsets, but often

perfectly fresh in marginal mines, so that even the hypersthene remained unchanged.

Two other points impressed themselves, the uniformity of the sulphides in the deposits, and the fact that the country rock had no influence on the character of the ore. Only three sulphide minerals showed themselves in appreciable amount at the mines, pyrrhotite, pentlandite and chalcopyrite; though they varied somewhat in proportions, more of the last mineral occurring in offsets than in marginal mines. The same three sulphides and no others formed the blebs of ore disseminated through the pyrrhotite-norite. The ore deposits rested on, or were enclosed in country rocks of great variety, such as quartzite, graywacke, granite, or greenstone, without the slightest effect on the ore, which consisted everywhere of the same three monotonous minerals. These relations were the same for the whole thirty-seven miles of the southern nickel range, showing that a single cause must have been at work to produce the ore deposits, a cause not connected with the rocks beneath the norite.

Finally, a study of the intrusive near the mines showed that pyrrhotite-norite was always present over large areas and that disseminated ores extended for miles along the edge of the norite in places where no ore body had been found. The blebs of ore were completely enclosed in rock and must have been present when the magma finally cooled; and the total amount of sulphides thus disseminated seemed much greater than the tonnage of ore in the mines. This ore, enclosed in norite with no sign of fissures or shearing through which fluids could circulate, must have been of magmatic origin; and so the geologists working on the map were forced to accept the theory of magmatic segregation as the only possible way of accounting for the facts.

Since the ore bodies always occur at the lowest points round the edge of the norite and ore is much heavier than rock, gravity seemed to play a large part in the segregation of the molten materials, especially in marginal deposits. In offsets, however, there was proof that hot solutions coming from the intrusive sheet and making their way through faulted and shattered zones had modified the deposits in important ways.

The theory that gradually took shape may be outlined briefly.

It begins with a great mass of magma far below the surface which makes its way up to the plane of weakness beneath the Animikie sediments and there spreads out as a sheet a mile and a quarter thick. The underlying floor of older rocks, left without support, collapses, and great faults extend in various directions, especially on the south side. Blanketed under 10,000 feet of sedimentary beds the molten mass cools very slowly allowing time for segregation to take place, norite sinking beneath the lighter micropegmatite, and the sulphides, much heavier and more fluid than the molten rock, settling toward the bottom, where much of it was caught as small particles in the cooling norite, while the rest escaped into depressions of the floor forming marginal deposits, or found its way under pressure into the fissures and crush breccias caused by the faults, forming offset deposits. Later hot waters from the cooling magma penetrated these openings in the country rock depositing quartz and carbonates and somewhat modifying the offset ores. In this process rare and precious metals, silver, gold and the platinum group, were concentrated along with copper ore in the narrower offset openings.

David Browne, the able metallurgist of the Canadian Copper Company, aptly compared the process to the pouring of his furnace products into slag pots, where clean slag collected on top, followed by a layer of slag filled with shots of sulphide, under which was the solid matte containing the nickel and copper.

The theory of magmatic segregation of rock and ore just suggested is really embodied in the map itself, which is meaningless on any other supposition, and it has been accepted by all the geologists who have taken any important part in tracing the geology of the nickel region. It is unquestionably the only theory which explains all the facts, including the immense quantity of sulphides distributed

through unchanged rock in the pyrrhotite-norite, and no theory which leaves more than half of the sulphides unaccounted for in the region should have any standing ground at all; yet a number of visitors to the mines, and even some geologists who have paid more attention to the greatly faulted southern range than to the general geology, have strongly advocated the hydrothermal theory, ignoring the evidence which proved absolutely convincing to the field geologists who spent years of work in producing what is admitted to be a fairly accurate map.

Most of the early field men have departed; but the three of them remaining, being puzzled by this curious state of affairs, decided to revisit Sudbury last summer and make a fresh study of typical sections, so as to test once more the magmatic theory to see if their earlier conclusions were wrong.

The results of their investigations follow.

Macroscopic and Microscopic Description of the Rocks of the Intrusive

These rocks have been described so frequently that only a brief account is called for at present. As one crosses from the basic border towards the centre of the syncline, the rocks, which at first are dark greenstones of medium grain, show little variation for from one-quarter to one-half of the length of the cross section, when they become lighter in colour and resemble pinkish syenite or granite. This change is accompanied by a drop in specific gravity from nearly 3 to about 2.6, with an increase of silica from about 50 to nearly 70 per cent. In all their traverses the writers have never observed a sharp break in passing from the basic rocks to the more acid varieties such as would suggest that the whole series was not a single genetic unit. The variation in specific gravity and silica content of suites of rocks taken across the eruptive at different points is graphically shown in Figs. 1 and 3 respectively.

Under the microscope many thin sections indicate an abundance of secondary hornblende, due to the total or partial alteration of the pyroxenes of the original rock. In every cross-section studied, some of the slides show fresh pyroxenes, of which hypersthene is always far more abundant than augite. As the hypersthene is always idiomorphic towards both plagioclase and augite, while the augite is xenomorphic toward the other two, it is usually not difficult to determine the type of pyroxene from which the secondary hornblende was derived. On the basis of such observations, the writers consider that the whole of the dark rock in its original fresh condition was norite, and suggest that this name should be applied to the whole basic facies. Of course the more altered parts would be more accurately designated as altered norite. (Plate I, Figs. 1 and 2.)

The rock of the acid border is micropegmatite or granophyre, and as seen under the microscope is largely composed of an intergrowth of quartz and feldspar often radiating from a well-defined crystal of plagioclase (Plate I, Fig. 3). In the micropegmatite the dark minerals are scantily represented by ill-defined scales of biotite, shreds of green hornblende, with smaller amounts of epidote and iron ores. Both acid and basic types are devoid of parallel structure, except where considerable shearing has occurred.

The plagioclase in the norite on the southern flank of the eruptive is very striking in thin sections, owing to its dusty brown colour. This is characteristic of hypersthene rocks and is supposed to be due to very fine inclusions of ilmenite. Thin sections from the norite of the northern flank of the eruptive do not exhibit this dusty brown type of plagioclase and as a result such norites are much lighter in colour. A sample of the brownish plagioclase from one of the specimens in the Cameron Mine section was separated first by gravity liquids, and finally purified by means of the magnetic separator of Hallimond. By means of this admirable machine it is possible to free the required sample from feldspars without inclusions on the one hand and from any particles with adhering dark minerals on the other. The chemical composition of the rock from which the sample was prepared is shown in

Analysis 66. The composition and density of the feldspar is shown in A.

	A
SiO_2	52.52
TiO_2	.23
Al_2O_3	29.23
Fe_2O_3 (total iron)	1.10
MgO	.39
MnO	.01
CaO	10.56
Na_2O	4.42
K_2O	.98
	99.44
S.G.	2.72

Neglecting the small amounts of those bases which do not enter into the formation of feldspars and calculating the composition of the plagioclase, one finds that if the albite molecule alone be considered the appropriate formula is $Ab_{43}An_{57}$, while if the orthoclase molecule be introduced as taking part in the plagioclase along with albite, the formula becomes $Ab_{46}An_{54}$. The former corresponds to average labradorite, and the latter somewhat more sodic but well above the labradorite-andesine boundary. Examination of the crushed mineral in immersion liquids shows that the extinction angles and indices of refraction vary somewhat due to the zoning so commonly observed in thin sections of norite. Most of the grains indicate a feldspar in the middle of the labradorite series.

The analysis shows that the cloudy brown dust so characteristic of the plagioclase in the norites of the south flank of the eruptive contains iron and titanium, and so supports the suggestion that these inclusions are ilmenite and hematite.

In order to determine the position of the rhombic pyroxene in the enstatite-hypersthene series, a sample for analysis was separated from the same powder from which the plagioclase was obtained. Here, too, the magnetic separator was employed to complete the purification of the mineral. The augite which remained with the rhombic mineral was readily removed from the rest of the powder owing to the occurrence in the former mineral of numerous tiny inclusions which appear to be magnetite, arranged in lines along the basal plane. The chemical nature of the mineral is shown in B.

	B	C
SiO_2	50.55	51.85
TiO_2	.57	.....
Al_2O_3	6.20	3.90
FeO (total iron)	16.90	20.20
MnO	.45	trace
MgO	21.65	21.91
CaO	1.16	1.60
Volatile	.....	.20
	97.48	99.66

Owing to the small quantity of the pure mineral available, no attempt was made to determine the constituents not shown in the analysis. The data are sufficient, however, to indicate that in the mineral the enstatite molecule is somewhat more abundant than that for hypersthene. The mineral is therefore bronzite rather than hypersthene. The composition of the pyroxene is very close to that from Château Richer analysed by Hunt.[1] (Analysis C.)

To determine the nature of the micrographic intergrowth which is the most abundant constituent in the acid differentiate, samples were separated from the last specimen on the acid border of the Levack section on the Canadian Pacific Railway (Analysis 63). Two samples were obtained by gravity differentiation and later purified by the magnetic separator, which picked out almost all the particles with adhering dark minerals. The specific gravity and composition of the two samples are shown in D and E.

[1]Hunt, T. S., Geol. Sur. Can., 1863, p. 468.

	D	E
SiO_2	74.00	76.64
Al_2O_3	14.04	12.38
Fe_2O_3	1.56	2.04
FeO	not determined	
CaO	1.10	.93
MgO	trace	trace
Na_2O	4.12	1.74
K_2O	5.56	6.72
	100.38	100.45
S.G.	2.597	2.619

The sample from which the intergrowth was separated had been crushed to pass the 100-mesh screen and rest on the 200. The microscopic examination of the selected material showed that practically all the grains were composite and that simple grains were practically absent. Calculations based on the analyses give the following mineral composition:

D		E	
Orthoclase	33.6	Orthoclase	40.4
$Ab_{85}An_{15}$	39.8	$Ab_{77}An_{23}$	19.5
Quartz	26.6	Quartz	40.1

These analyses point to a variation in the type of feldspar in the intergrowth and in the ratio of quartz to feldspar, to the probability that anorthoclase is a prominent element in the feldspar complex and raise the question as to whether such intergrowths are eutectic in nature.

The intergrowth of quartz and feldspar commonly radiates from a phenocryst of plagioclase. The feldspar of the intergrowth often extinguishes in areas at the same position as one part of the twin crystal, indicating that feldspar of the micropegmatite is optically continuous with that of the phenocryst. As first shown by Walker,[1] the feldspar of the intergrowth sometimes shows parallel twinning according to the albite law. These facts seem to indicate that the feldspar

[1]Walker, T. L., Quart. Jour. Geol. Soc., vol. 53, p. 55.

of the intergrowth is sometimes plagioclase, as does the high percentage of soda shown in the analyses of the intergrowth. The graphic intergrowth is found not only in the most acid portions of the intrusive, but also in small amounts in most of the dark rocks, gradually increasing in amount as the micropegmatite is approached. (Plate I, Fig. 3.)

The hornblende in these rocks is mostly secondary after pyroxene, though in some of the norites it appears in small amount as an original constituent. In the more basic norites biotite is common as dark brown, strongly pleochroic individuals containing large inclusions of magnetite and numerous pleochroic haloes. In the acid rocks this mineral is represented by small flakes and scales.

Secondary alteration in the rocks of the nickel eruptive is indicated by the development of epidote in the feldspars, alteration of the pyroxenes, occasional bleaching of the biotite and in the formation of small amounts of epidote and a carbonate, probably calcite. The alteration is not always most marked on the basic border in close proximity to the sulphide deposits as suggested by some advocates of the hydrothermal origin of the ore bodies. The writers have examined thin sections of very fresh norite, from the workings of the Creighton, Murray and Blezard mines, in which most of the hypersthene was unusually fresh. In other instances the best occurrences of fresh norite may be observed at some distance from the basic border, as, for example, some two miles west of the Murray mine on the main line of the Canadian Pacific Railway.

Is the Sudbury Rock Norite?

Recently Phemister[1] has criticized the use of the name norite as applied to the basic phase of the nickel eruptive. The name was first used for these rocks by Walker[2] in 1897. At the time it was well known that most thin sections did not show any fresh hypersthene, and that those with hypersthene commonly contained a minor amount of monoclinic pyroxene. In those sections which showed secondary hornblende instead of pyroxene, it is usually quite plain that most of this mineral was derived from hypersthene. The rhombic mineral is more or less idiomorphic, while the augite is later than both the plagioclase and hypersthene, and is xenomorphic toward them. Moreover, there are all stages of alteration of these pyroxenes, which makes it easy, as a rule, to indicate the source of the hornblende. Walker, under the guidance of Zirkel, felt at that time that norite might be used to designate a granitoid rock of the gabbro family in which the rhombic pyroxene was always far more abundant than the monoclinic, even where in many parts the whole of the pyroxene had been changed to hornblende. At best rock species are so ill-defined compared with those of the biologist that it is usually possible to use more than one name with equal accuracy for the same specimen (Plate I, Figs. 1 and 2). Phemister, in his reports, regards this rock as gabbro or "norite," while others have thought quartz-diorite or diorite preferable. He has maintained that the Sudbury rock is too acid to be called norite. It does, as a fact, often contain a little quartz, but a comparison of the more basic Sudbury norites in the analyses contained in this paper with the average of five analyses from the Bushveld norite as prepared by Daly or with Washington's average of 24 norites from different parts of the world, will show that while at Sudbury the silica is often only 50 per cent. and occasionally 47 per cent., the Bushveld norite average is 52 per cent. and the world average of Washington 50 per cent.

The following analyses indicate the composition of the Sudbury norite, of the norite from the Bushveld, and of norites from various parts of the world.

[1] Phemister, T. C., Ont. Dept. Mines, Vol. XXXIV, Part 8.
[2] Walker, T. L., *Op. cit.*, p. 49.

	F	G	H
SiO_2	52.33	52.05	50.39
TiO_2	1.88	.21	1.13
Al_2O_3	14.93	17.24	16.06
Fe_2O_3	3.22	.65	2.43
FeO	8.31	6.65	7.86
CaO	6.99	11.37	9.20
MgO	4.13	8.98	8.37
MnO	.14	.24	.17
Na_2O	3.25	1.83	2.61
K_2O	2.10	.40	.79
H_2O	1.67	.89	.79
CO_2	.11	.....	.....
P_2O_5	1.06	.12	.20
S	.13	.....	.....
	100.25	100.63	100.00

F. Average of 5 analyses of norite from the basic border in the Levack section (Analyses 50-54).

G. Average of 5 analyses from the Bushveld (Daly, R. A., Bull. G.S.A., vol. 39, p. 727).

H. Washington's average of 24 norites from all parts of the world quoted by Daly.

It is felt by the writers that the new analyses of the rocks across four sections, submitted in this paper, offer a better guide as to the chemical composition and variation of the Sudbury intrusive than the small number of older analyses or the calculations of mineral and chemical composition based on the study of thin sections under the microscope. They are still of the opinion that norite is the best name for the basic member of the nickel intrusive.

Chemical Analyses of the Nickel-Bearing Intrusive

The first analyses of these rocks were published by Walker[1] in support of his contention that there was a genetic relationship between the norite and micropegmatite and that there was a gradual transition from the basic to the acid border. These analyses (1-5) were from the section from Blezard mine to Whitson Lake.

[1]Walker, T. L., Quart. Jour. Geol. Soc., 1897, vol. 53, p. 56.

CHEMICAL COMPOSITION OF THE ROCKS OF THE BLEZARD MINE SECTION

	1	2	3	4	5
SiO_2	49.90	51.52	64.85	69.27	67.76
TiO_2	1.47	1.39	.....	.78	.46
P_2O_5	.17	.10	.24	.06	.19
Al_2O_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	.91	1.00
MnO	trace	trace	trace	trace	trace
K_2O	2.25	.70	3.02	3.05	1.19
Na_2O	1.82	2.66	3.92	3.12	5.22
H_2O	.76	1.68	.78	.76	1.01
	99.03	99.71	98.30	99.35	100.29
S.G.	3.026	2.832	2.788	2.724	2.709

The eruptive represented by the above analyses is two and a half miles wide. Until 1923 this was the only series of analyses across the whole width of the eruptive taken as a continuous series. Chemically, all conclusions as to the variation from one edge to the other were based on this series prior to 1923.

In his report on the geology of the Sudbury region, Coleman[1] added a number of new analyses of norite and micropegmatite, but they do not constitute a series from top to bottom.

In 1917 Knight[2] assembled the ten analyses contained in the papers by Walker and Coleman, arranging them in a series from basic to acid, and concluded that "the middle portion of the intrusive is even more acid than part of the inner edge itself." It should be noted in this connection that the ten analyses brought together by Knight were not all from the same section, but from four different sections, in some instances over twenty miles apart, and that some of Coleman's analyses were made on unusual specimens like

[1]Coleman, A. P., Bureau of Mines, Ont., 1905, p. 116.

[2]Knight, C. W., Ont. Nickel Commission, 1917, pp. 117-118.

that on a dark rock from the Creighton mine, showing microcline in sections, or a schistose greenstone from near Fairbanks Lake.

In the same report Knight publishes 14 new analyses of the norite from sections northwest from the Creighton and Murray mines. The former series of seven analyses covered a distance of 3,250 feet from the Creighton, where the whole section in a northwesterly direction is about four and a half miles. The latter series, taken along the Canadian Pacific Railway northwest from the Murray mine, covered a distance of 1,900 feet, the whole distance across the eruptive at this point being about three and a half miles. These series of analyses, therefore, cover about one-eighth of the whole section in the former case and about one-tenth in the latter. They were not designed to indicate the chemical relationship of the intrusive as a whole but merely the degree of differentiation in the outer edge of the norite. These analyses are given in 6-12 for the Creighton section and 13-19 for the Murray section. They range from 51.34 per cent. to 56.10 per cent. of silica. From these analyses Knight rightly observes that for these two sections no marked differentiation is shown in the marginal facies of the norite.

TABLE SHOWING CHEMICAL COMPOSITION OF NORITE NORTHWEST OF THE CREIGHTON MINE

	6	7	8	9	10	11	12
SiO_2	55.58	51.34	51.80	55.24	54.12	53.26	54.84
Al_2O_3	.....	.....	.....	.....	20.18	17.40	.....
Fe_2O_3	2.32	2.51	2.80	1.42	2.65	3.35	1.42
FeO	8.03	8.19	7.92	7.07	5.80	5.72	5.67
CaO	7.20	7.40	6.72	6.72	6.72	8.00	7.25
MgO	.69	3.95	3.36	1.13	3.81	6.62	1.56
Na_2O	2.56	2.18	1.84	2.74	3.17	2.64	2.88
K_2O	.98	.80	.62	1.04	1.52	1.27	1.38
CO_2	.21	.32	.39	.22	.40	.31	.33
H_2O	2.54	.78	3.59	1.04	1.74	1.71	1.72
	.....	.....	.....	.....	100.11	100.28	.....

6, 140 feet northwest of open pit.
7, 200 " " "
8, 300 " " "
9, 750 " " "
10,1,200 " " "
11,2,000 " " "
12,3,250 " " "

TABLE SHOWING CHEMICAL COMPOSITION OF NORITE NORTHWEST OF THE MURRAY MINE

	13	14	15	16	17	18	19
SiO_2	54.84	54.81	55.96	56.10	51.78	54.08	53.08
Al_2O_3	15.82	16.98	21.84	18.72	20.90	16.72	18.54
Fe_2O_3	3.36	1.82	2.84	2.42	1.82	4.90	2.26
FeO	7.02	6.67	5.55	5.78	6.54	5.88	5.28
CaO	5.71	6.96	6.52	6.67	7.52	7.53	7.51
MgO	6.02	6.07	1.48	5.08	5.77	5.23	6.18
Na_2O	3.87	2.99	2.58	2.25	2.82	2.79	3.35
K_2O	2.31	2.18	1.79	1.96	1.84	1.55	2.41
CO_2	trace	.17	trace	.22	trace	.42	trace
H_2O	1.27	1.87	1.19	1.29	1.31	1.08	1.41
	100.22	100.52	99.75	100.49	100.30	100.18	100.02

13, 30 feet northwest of basic edge.
14, 150 " " "
15, 300 " " "
16, 600 " " "
17, 900 " " "
18,1,400 " " "
19,1,900 " " "

In 1923 Knight[1] published an article on the chemical composition of the norite-micropegmatite as shown on lots 11 and 12 in the third concession of MacLennan township. While the intrusive is here 8,300 feet across, the seventeen analyses cover only 7,000 feet, beginning at 100 feet from the outer or basic border. In explanation of the omission of 1,200 feet from the acid border the writer states that "it is probable that it would not be safe, for purposes of chemical analysis, to take a sample any nearer the edge than about

[1]Knight, C. W., Econ. Geol., Vol. XVIII, 1923, pp. 592-594.

1,200 feet owing to the fact that the micropegmatite has absorbed part of the sediments with which it is in contact on the inner edge." These analyses are given below, 20-36.

CHEMICAL COMPOSITION OF ROCKS, MACLENNAN TOWNSHIP SECTION

	20	21	22	23	24	25	26	27	28
SiO_2.....	56.21	57.10	57.74	58.19	53.14	52.86	66.05	69.08	67.80
Al_2O_3....	22.85	15.93	19.93	18.67	23.17	18.34	11.46	11.55	14.32
Fe_2O_3....	1.25	4.40	1.51	2.28	.71	4.67	5.95	5.55	4.36
FeO.....	4.80	4.87	5.36	5.72	7.02	7.99	3.79	2.98	3.22
CaO.....	4.22	5.35	5.67	6.62	5.20	5.57	2.25	2.10	1.44
MgO....	1.24	4.74	1.95	2.32	2.68	3.45	..80	.80	1.16
Na_2O....	3.69	3.24	3.28	3.08	4.20	4.52	4.44	3.66	3.05
K_2O.....	3.45	1.92	1.67	1.48	2.14	.79	3.60	2.66	3.14
H_2O.....	2.56	2.55	2.67	1.88	1.73	1.79	1.84	1.30	1.46
CO_2.....	.....	.20	.31	.16	.18	.18	.....	.24	.24
	100.27	100.30	100.09	100.40	100.17	100.16	100.18	99.92	100.19

	29	30	31	32	33	34	35	36
SiO_2.....	69.10	68.76	69.84	66.58	66.50	67.40	64.04	68.50
Al_2O_3....	13.95	14.55	11.90	11.79	15.26	15.01	14.89	12.57
Fe_2O_3....	2.93	2.40	4.00	5.08	1.61	1.94	4.14	2.37
FeO.....	3.43	4.04	3.74	4.51	4.28	4.62	5.71	5.13
CaO.....	1.08	1.65	1.64	1.95	2.26	2.07	2.27	2.07
MgO....	1.15	.67	.72	1.44	1.88	1.13	.97	1.09
Na_2O....	3.64	3.21	3.44	3.33	3.40	2.94	3.73	3.27
K_2O.....	3.58	3.58	3.27	3.66	3.16	3.37	2.43	3.30
H_2O.....	1.10	1.22	1.38	1.62	1.66	1.65	1.93	1.64
CO_2.....	.21	trace	.26	0.25	.18	.17	trace	.27
	100.17	100.08	100.19	100.21	100.19	100.30	100.11	100.21

These samples, beginning with No. 20, are 100, 300, 1200, 1500, 1800, 2100, 2600, 2900, 3500, 4000, 4600, 4900, 5800, 6200, 6500, 6800 and 7100 feet, respectively, from the outer edge of the norite-micropegmatite.

Knight states, in referring to the results obtained, that "the analyses show, further, that the most basic part of the eruptive is not along the outside edge, but from 1,500 to 2,100 feet from the outside edge. The analyses also show that the most acid part is not along the inner edge, but from

3,400 to 4,300 feet from the inner edge, indeed, nearer the centre than the edge. In other words, the transition from basic to acid facies is not a gradual one."

It would be better in accord with the analyses to state that, in the MacLennan township section, so far as the section extends, (*a*) the most basic rocks probably are found between 1,500 and 2,600 feet from the basic edge, (*b*) from 2,600 to 7,100 feet from the basic edge the micropegmatite is very constant, the silica varying between 64.04 per cent. and 69.84 per cent., (*c*) there may be more basic norite in the first 100 feet, and (*d*) since the composition of the last 1,200 feet on the acid border is not known, it may possibly be more acid than any of the samples analysed. It is not safe to speak of the composition of the eruptive, as a whole, when there is no evidence of the character of the first hundred feet on the basic border or of the last 1,200 feet on the acid border.

On account of the lack of complete data regarding the chemical variation of the rocks of the nickel eruptive from top to bottom, the writers decided to arrange for the analysis of suites of specimens taken to represent four complete sections, two on the northern side of the field and two on the southern. These analyses have been made by Mr. M. C. Haller and Mr. A. R. Graham, research assistants in the Department of Mineralogy of the University of Toronto, and by Mr. J. A. M. Dawson.

Analyses by Haller: 39, 40, 41, 43, 44, 46, 47, 49, 50, 51, 52, 53, 54, 56, 57. 58, 59, 61, 63, 64, 65, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 78, 79, 80, 81, A, B, D, E.

Analyses by Graham: 37, 38, 42, 45, 48, 55, 60, 62, 66, 77.

Analyses by Dawson: Most of the silica determinations shown in the graph for the Creighton section in Fig. 1, and 82 to 92.

The specimens analysed were all taken at known distances from the borders, as indicated relatively in the graphs contained in Fig. 1, and in the data following each series of analyses. The specimens used in the preparation of the samples for analysis and for the determination of specific gravity were usually hand specimens weighing from one to two pounds. The crushed and ground samples were exposed to the air to dry for twenty-four hours prior to analysis.

The Capreol Section

This series was collected along the crossing of the Canadian National Railway north of Capreol, where the eruptive is about one and a half miles wide. Analyses 37-49.

The analyses indicate a very gradual and ordered increase in acidity from the rock on the northern border (38) to the southern contact with the older rocks. The norite is not so basic as shown in some sections. The only break in the ordered succession is shown by the last specimen of the series (49) which may be due to some assimilation of the overlying rock. No. 37 is an older basic rock which forms a breccia in the gneissoid granite north of the margin of the norite.

CHEMICAL COMPOSITION OF THE ROCKS OF THE CAPREOL SECTION

	37	38	39	40	41	42	43	44	45	46	47	48	49
SiO_2	50.06	57.78	58.13	59.15	59.65	59.34	61.97	64.10	68.92	68.15	69.55	69.60	65.22
TiO_2	.91	.95	1.13	.66	.64	.80	.98	1.26	.41	.36	.33	.44	.19
Al_2O_3	15.02	17.25	15.78	15.44	15.50	15.22	13.60	12.64	11.80	11.53	12.76	12.40	16.08
Fe_2O_3	1.41	1.25	1.11	1.74	1.61	1.34	2.72	2.68	2.44	1.80	1.06	1.67	.60
FeO	8.92	5.73	5.32	5.40	5.54	5.66	6.40	5.40	3.68	4.40	3.54	3.11	4.82
CaO	10.25	6.16	5.41	5.85	6.40	7.07	3.97	2.11	2.16	1.58	1.53	2.54	1.53
MgO	8.21	4.20	4.79	4.19	3.90	3.88	2.37	2.54	1.60	1.89	2.64	1.67	2.15
MnO	.15	.08	.13	.14	.18	.10	.09	.11	.03	.05	.03	.03	.03
Na_2O	2.28	3.08	2.95	3.09	2.75	2.73	2.86	3.52	3.15	2.94	4.10	5.17	2.96
K_2O	1.10	1.97	2.23	1.96	2.50	1.91	2.72	3.52	3.93	4.66	3.26	1.25	4.00
H_2O	1.64	1.80	2.36	1.76	1.46	1.57	1.84	1.95	1.56	1.64	1.28	1.59	1.85
CO_2	.08	.03	.10	.09	.32	.12	....	.09	.23	.67	.20	.59	.05
P_2O_5	.06	.14	.23	.16	.18	.18	.53	.26	.17	.14	.20	.15	.19
S	.11	.06	.06	.16	.06	.06	.12	.07	.04	.04	.01	.00	.04
	100.20	100.48	99.73	99.79	100.69	99.98	100.17	100.25	100.12	99.85	100.49	100.21	99.71
O eq. of S	.06	.03	.03	.08	.03	.03	.06	.04	.02	.02	....	..	.02
	100.14	100.45	99.70	99.71	100.66	99.95	100.11	100.21	100.10	99.83	100.49	100.21	99.69
S.G.	2.930	2.815	2.795	2.815	2.815	2.795	2.78	2.685	2.665	2.670	2.670	2.705	2.705
Yards		0	55	158	367	424	535	609	741	1019	1305	1481	2559

CHEMICAL COMPOSITION OF THE ROCKS OF THE LEVACK SECTION

	50	51	52	53	54	55	56	57	58	59	60	61	62	63
SiO_2	55.32	50.02	50.74	50.80	54.78	68.06	67.04	69.20	63.66	63.97	63.29	69.26	67.22	69.38
TiO_2	.75	1.98	1.83	3.37	1.47	.38	.64	.71	.77	.84	.79	1.06	.69	.74
Al_2O_3	14.50	14.02	16.04	14.75	15.32	12.71	13.46	12.67	14.69	15.05	13.33	13.07	12.62	12.73
Fe_2O_3	4.34	4.17	2.58	3.36	1.64	1.56	2.34	.94	3.65	.70	2.10	.54	2.80	.70
FeO	5.39	9.14	8.58	9.44	9.00	4.76	3.02	3.66	3.52	5.48	5.47	4.78	3.71	4.64
CaO	7.97	8.66	8.19	6.27	3.84	2.49	2.12	1.79	2.04	3.05	4.06	1.57	5.38	1.63
MgO	4.82	4.52	4.46	4.38	2.45	1.05	1.06	1.12	1.76	2.19	1.87	1.28	.85	1.25
MnO	.10	.14	.11	.16	.18	.05	.09	.09	.11	.12	.14	.12	.13	.11
Na_2O	3.07	2.44	2.92	2.96	4.86	4.00	3.26	3.38	3.64	3.76	3.52	1.96	2.28	2.96
K_2O	1.60	1.50	1.68	1.92	3.78	3.66	4.92	4.50	4.04	3.44	3.73	5.48	3.15	4.12
H_2O	2.02	1.28	1.45	1.63	1.99	1.07	1.59	1.38	1.62	1.61	1.45	1.04	1.00	1.78
CO_2	.31	.06	.05	.06	.06	.13	.05	.03	.03	.04	.05	.08	.15	.05
P_2O_5	.06	1.66	1.64	1.36	.56	.14	.19	.28	.34	.27	.24	.20	.11	.20
S	.20	.12	.13	.12	.10	.02	.06	.02	.04	.05	.07	.03	.06	.03
	100.45	99.71	100.40	100.58	100.03	100.08	99.84	99.77	99.91	100.57	100.11	100.47	100.15	100.32
O eq. of S	.10	.06	.07	.06	.05	.01	.03	.01	.02	.03	.04	.02	.03	.02
	100.35	99.65	100.33	100.52	99.98	100.07	99.81	99.76	99.89	100.54	100.07	100.45	100.12	100.30
S.G.	2.82	2.94	2.91	2.93	2.80	2.68	2.66	2.67	2.68	2.72	2.74	2.69	2.69	2.68
Yards	57	475	513	551	665	931	1521	2337	3021	3173	3401	3821	4047	4123

The Levack Section

Fourteen specimens were collected along the main line of the Canadian Pacific Railway, extending over a distance of nearly two and a half miles although the contact was not observed at either end of the section. The analyses and specific gravities are shown in Nos. 50 to 63. The distances from the first of the norite outcrops to the point where each of the specimens was collected is shown in yards below the table of analyses.

The specimen taken nearest the contact of the norite and gneiss is slightly more acid than the three following which represent the norite in its more basic form. While there is little variation in the micropegmatite, it may be noted that the specimen richest in silica comes from the extreme acid edge, a fact to which little importance should be attached had it not been so often stated on the basis of the small number of older analyses, that the most acid type does not occur on the inner margin but some distance from the upper contact. It would be better to dwell on the lack of ordered variation inside the micropegmatite after the transition from the norite has been definitely established.

CHEMICAL COMPOSITION OF THE ROCKS OF THE CAMERON MINE SECTION

	64	65	66	67	68	69	70	71	72	73	74
SiO_2	51.53	53.68	54.68	54.72	47.22	58.54	63.29	74.24	69.17	69.29	70.32
TiO_2	.36	.39	.38	.48	3.20	1.50	1.36	.36	.64	.96	.98
Al_2O_3	11.23	16.47	18.63	17.55	14.72	14.83	13.59	9.26	12.52	12.82	12.05
Fe_2O_3	1.48	1.72	1.13	1.42	3.90	1.56	1.80	.16	.16	1.02	1.48
FeO	7.32	5.64	5.59	5.34	9.72	7.88	5.64	5.64	6.06	4.36	4.92
CaO	12.82	7.64	8.62	7.86	8.14	4.26	3.36	.58	1.40	2.37	1.41
MgO	12.50	7.98	6.73	6.32	4.72	2.92	2.31	1.01	1.84	1.53	1.53
MnO	.17	.12	.14	.12	.15	.14	.11	.09	.06	.09	.12
Na_2O	1.32	2.76	2.79	2.70	2.68	3.42	3.12	2.92	4.26	3.64	2.92
K_2O	.56	1.32	1.03	1.36	1.56	3.34	4.04	4.66	2.24	3.12	3.78
H_2O	.67	1.71	.58	1.56	1.52	.86	.88	.61	1.17	.66	.67
CO_2	.09	.37	.03	.06	.78	.05	.06	.08	.05	.10	.04
P_2O_5	.10	.41	.06	.22	1.24	.52	.34	.05	.14	.10	.20
S	.08	.13	.07	.19	.22	.12	.04	.02	.03	.02	.03
	100.23	100.34	100.46	99.90	99.77	99.94	99.94	99.68	99.74	100.08	100.45
O eq. of S	.04	.07	.04	.10	.11	.06	.02	.01	.02	.01	.02
	100.19	100.27	100.42	99.80	99.66	99.88	99.92	99.67	99.72	100.07	100.43
S.G.	3.01	2.78	2.82	2.82	2.94	2.83	2.77	2.66	2.72	2.71	2.71

The Cameron Mine Section

A series of eleven specimens was collected by Mr. H. C. Rickaby of the Ontario Department of Mines, along a line from the Cameron mine in lot 6, concession I to lot 8, concession IV in the township of Blezard, where the eruptive is about three miles wide. The specimens were taken at regular intervals of a little more than a quarter of a mile. These specimens have been analysed with the result shown in 64-74.

From the above series of analyses it appears that the five analyses on the basic border average about 52 per cent. of silica, which is about the general average of norite. No. 71, which is out of harmony with the rest of the series, is a granite quite different from the acid types on the nickel eruptive, and is regarded as a representative of the younger granite which is later than the eruptive and at times intrusive into it. Phemister,[1] in his account of the Sudbury-Capreol road section, which probably crosses the present section, also refers to the presence of intrusions of granite in the micropegmatite. With the omission of No. 71 the analyses show a gradual transition from the noritic to the micropegmatitic phase. This section is only about two miles west of the section from which Walker's original series of specimens was obtained on which the argument for the differentiation of the eruptive was founded. (Analysis 1-5.)

The Creighton Section

As study of this series of specimens has not been completed, there are, in the analyses as presented, some very long intervals between specimens, particularly in the acid part of the intrusive (Analyses 82-92). While the most basic rocks in this series are over three thousand yards from the basic border, a specimen collected about two chains from the northern margin of the great pit at the Creighton mine and not yet completely analysed, contains only 51.50 per cent. of silica. The curve for the silica content for the whole

[1] Phemister, T. C., Ont. Dept. of Mines, 34, Part 8, p. 12.

CHEMICAL COMPOSITION OF THE ROCKS OF THE CREIGHTON MINE SECTION

	82	83	84	85	86	87	88	89	90	91	92
SiO_2	70.44	72.60	66.43	51.60	51.62	55.16	54.17	54.92	56.60	56.34	56.50
TiO_2	1.29	.31	.30	1.18	.90	.62	.44	.48	.56	.47	1.33
Al_2O_3	12.14	13.09	13.79	17.16	16.85	18.09	19.64	17.55	17.60	18.11	16.13
Fe_2O_3	.67	.60	1.48	2.97	1.95	.70	.61	1.03	.82	1.01	.65
FeO	4.72	2.88	5.56	9.52	8.06	5.63	6.03	6.35	6.32	6.14	6.68
CaO	1.74	1.25	1.93	7.85	8.87	7.82	8.32	7.68	6.90	6.65	7.22
MgO	1.16	.56	1.80	4.07	6.35	6.66	5.93	6.62	5.51	5.57	6.34
MnO	.05	Trace	.09	.09	.11	.11	.09	.12	.13	.11	.13
Na_2O	2.97	3.59	3.01	2.43	2.77	2.83	2.52	2.48	2.72	2.54	2.39
K_2O	4.01	4.19	3.64	1.17	.57	1.07	.76	1.09	1.52	1.74	1.54
H_2O	.02	.02	.16	.06	.05	.09	.08	.06	.06	.05	.06
H_2O	.49	.58	1.66	.49	.71	1.03	.77	.81	.58	.62	.81
CO_2	.24	.54	.05	.09	.21	.12	.09	.07	.08	.03	.11
P_2O_5	.23	.10	.35	.87	.46	.18	.22	.17	.18	.13	.20
S	.16	.07	.07	.20	.14	.07	.13	.08	.10	.09	.08
Total	100.33	100.38	100.32	99.75	99.62	100.18	99.80	99.51	99.68	99.60	100.17
Yards	8360	5632	4026	3762	3058	2178	1672	1298	924	682	484

series collected is shown in Figure 1. In this section there are several intrusions of younger granite which, as seen under the microscope, are not to be confused with the micropegmatite, as has been done occasionally. These granites are practically free from the characteristic intergrowth of quartz and feldspar while the acid differentiate of the nickel-bearing intrusive is largely composed of such intergrowth.

The percentage of silica in Analyses 1-74 and 82-92 is indicated graphically for the eight series of analyses made to show the variation in chemical composition in cross section (Fig. 1). The sections have been reduced so that all appear to have the same length, and where only a part of the section has been analysed, as in Nos. 3, 7 and 8, it is so indicated. The graph, No. 5, representing the silica content of the succession of specimens collected from the section north of the Creighton mine indicates in one case an unusually high acidity—74 per cent.—possibly due to an intrusion of younger granite. The complete analyses of this series of rocks is not yet available. In three of the sections the most basic rock appears to be on the border, while in the others more basic types of norite occur at some distance removed. There are many examples of rocks intermediate between the norite and micropegmatite with silica ranging from 57 to 63 per cent. Inside the micropegmatite the rocks range within narrow limits from 63 to 70 per cent. silica. Sometimes the most acid type is on the inner border, at other times toward the middle of the acid member. This graph is based on the analyses given in detail on the previous pages, and has no value apart from giving in one picture the data as to variation in acidity of the eruptive so far as known at the present time.

Is the Norite-Micropegmatite One or Two Intrusives?

In 1916 Harker[1], in discussing differentiation of rock magmas in deep reservoirs suggested that some of the popular examples of differentiation *in situ* after intrusion might be

[1] Harker, A., Jour. Geol. vol. 24, 1916, p. 555.

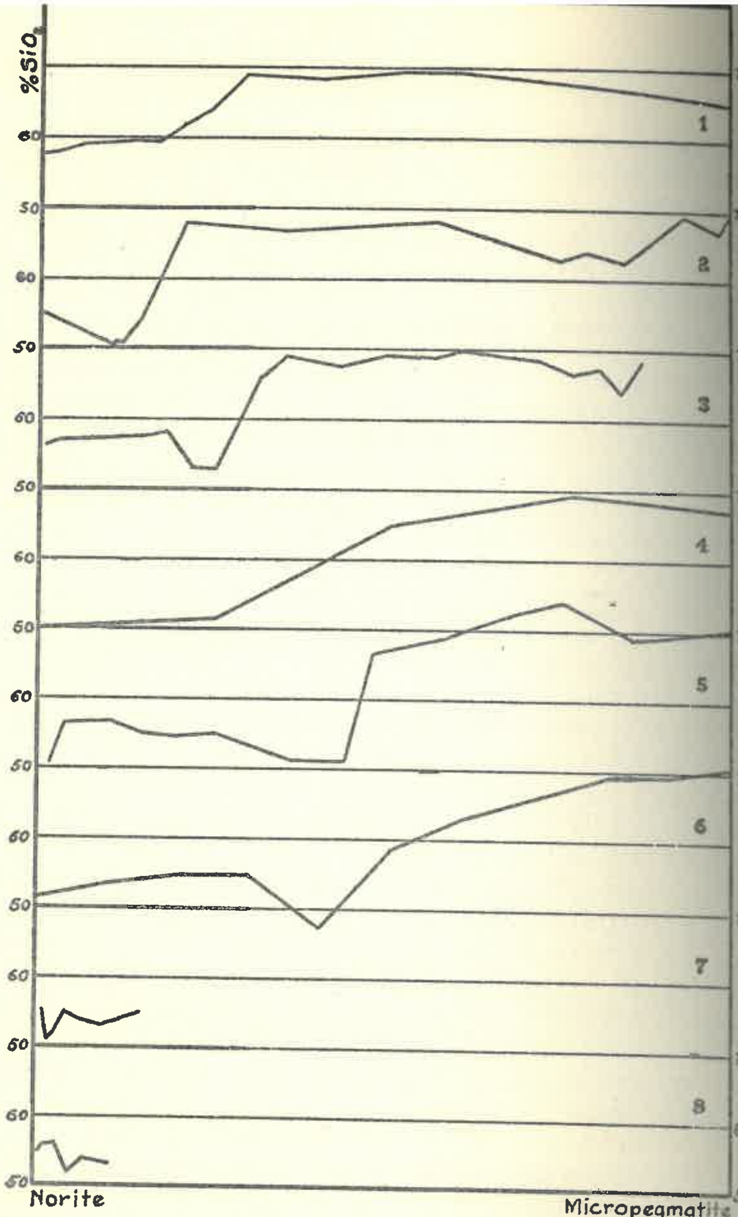


FIG. 1

Graph representing the variation in silica across the norite-micropegmatite in eight sections as follows:

1. Nandair to Capreol on the C.N.Ry. 2. Levack eastward on the C.P.Ry. 3. MacLennan Township section. 4. Blezard Mine to Whitson Lake. 5. North from the Creighton Mine. 6. North from the Cameron Mine. 7. Northwest from the Creighton Mine. 8. C.P.Ry. northwest of the Murray Mine.

explained as due to successive intrusions, a later acid magma possibly from the same reservoir following a basic one before the latter, already solid, had had time to cool. In this connection he referred modestly to the Sudbury intrusion as follows:

> Where an overlying sheet is separated from an underlying one by a surface of discontinuity I see no explanation but that of distinct intrusions. Nor is this explanation necessarily excluded, even when no sharp division is seen, for, under appropriate conditions, a transitional zone may result from partial admixture. The Sudbury laccolite is probably a case in point though I must confess to only a limited personal examination of the mass. I found no indication of a regular "composition gradient" in either the norite or granophyre, considered separately, while the transitional zone between them has all the characteristics of a hybrid rock.

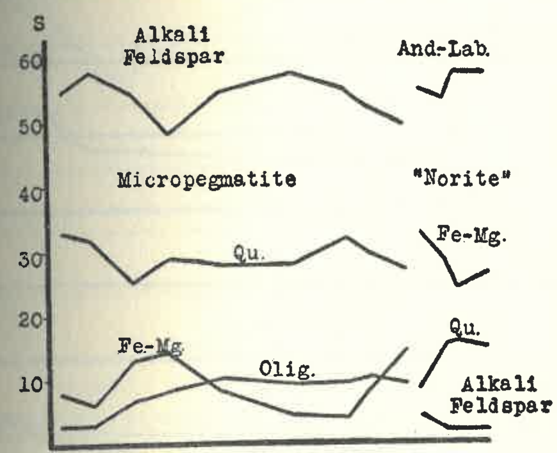


FIG. 2

Curve of mineralogical variation across the Levack traverse. In this graph the alkali feldspar is said to be dominantly potassic (after Phemister).

The question raised by Harker was adopted by Phemister[1] as a thesis. In the field he collected specimens from eleven traverses across the eruptive, and later studied them microscopically, but does not appear to have made any chemical

[1] Phemister, T. C., Ont. Dept. Mines, vol. 34, Part 8 .

analyses. With the microscope he determined the proportions of the principal minerals, and found that there was a sharp break as to kinds and proportions of minerals when passing from the "norite" to the micropegmatite. In only one instance did he, in the field, recognize a sharp contact between the two rock types to support the mineralogical break as determined by the study of thin sections. The mineralogical variation across the eruptive was in each case represented by a graph. Figure 2 is a reproduction of his graph for the section along the Canadian Pacific Railway near Levack.

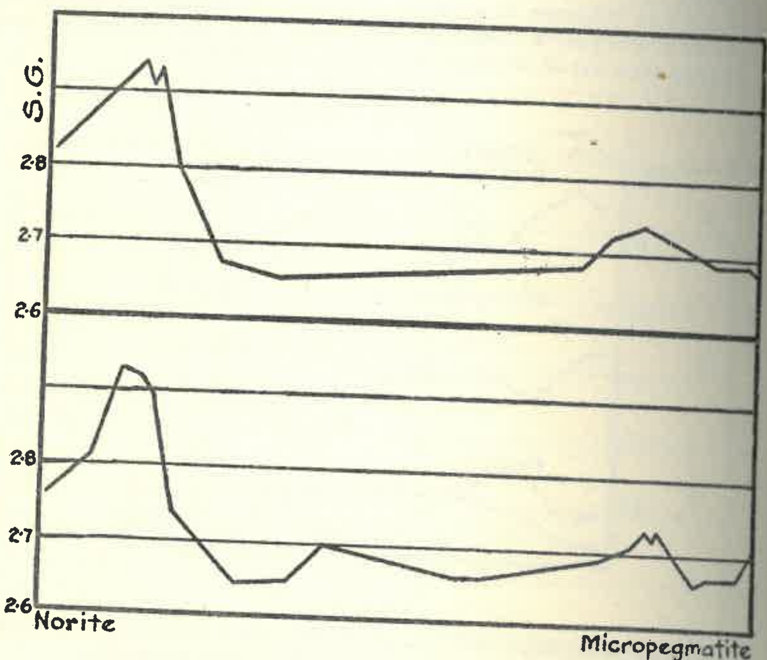


FIG. 3

Two series of specimens were taken along the Canadian Pacific Railway east of Levack. The specific gravities of the specimens in both are represented in these curves.

During the summer of 1928 Walker collected a series of specimens from this same section as did Mr. A. G. Burrows

Provincial Geologist of Ontario. Figure 3 shows the variation in specific gravity across the eruptive for these two suites of specimens. The close resemblance shown by these graphs suggests that the series collected by Phemister, which is mineralogically indicated in Figure 2, was probably nearly identical with the two collected in 1928.

Assuming that Phemister's series of specimens was very much like the one studied by us, the analyses of which are indicated in Nos. 50 to 63, it is of interest to compare his quantitative mineral analysis with the chemical data submitted herewith.

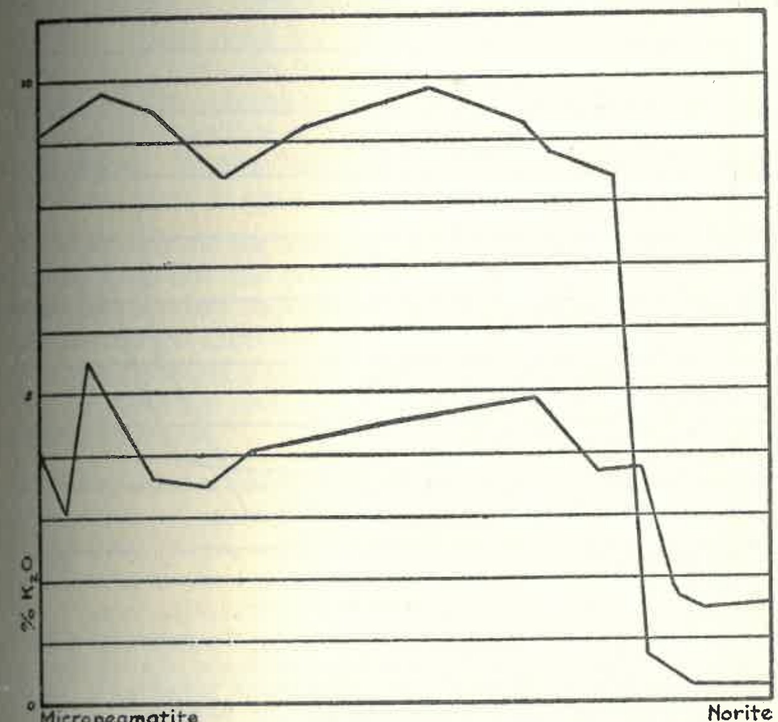


FIG. 4

The amount of potash contained in the alkali felspar in Fig. 2 is plotted above, the lower curve represents the potash found by chemical analysis in the series of specmens collected by Walker along the same section of the railway.

The proportion of alkali feldspar found by Phemister in the acid part of the eruptive is much greater than one would expect from the chemical data, while in the basic portion it is far less. As the alkali feldspar is said to be "dominantly potassic" the writers have calculated the percentage of potash which should be found on the basis of his mineral analysis. In Figure 4 the variation in potash across the eruptive is shown for the amount of alkali felspar indicated by Phemister and for the percentages shown in Analyses 50-63. The chemical data indicate only about one-half the potash which Phemister shows for the acid part of the eruptive but about seven times as much in the basic border.

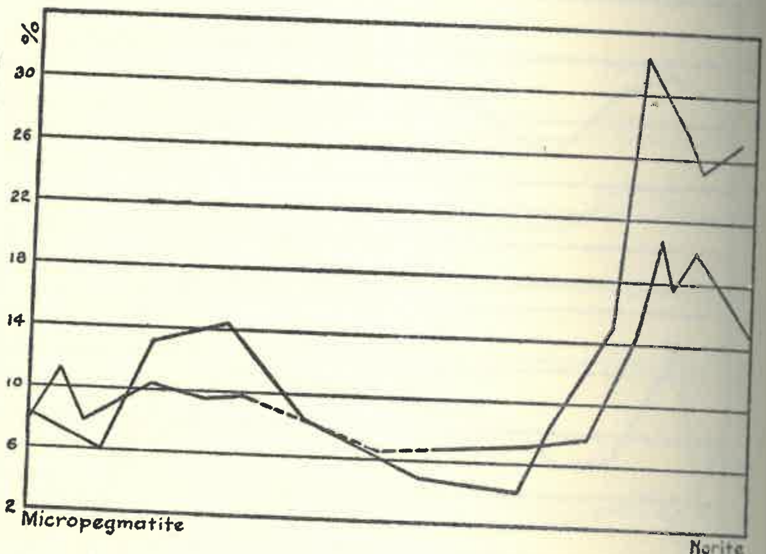


FIG. 5

The curve with the unbroken lines represents the percentage of Mg-Fe minerals found by Phemister in the series of specimens collected along the railway east of Levack; the other curve represents the percentage of *only* five constituents which are found in such minerals, viz., Fe_2O_3, FeO, MgO, TiO_2 and MnO.

In Figure 2 the proportions of Mg-Fe minerals are indicated. These minerals must include all the oxides of iron, manganese, magnesium, titanium, and probably part of the lime and alumina in addition to considerable silica. The minerals represented are chiefly various pyroxenes, hornblende, biotite, epidote, magnetite, ilmenite, pyrrhotite, and apatite. Figure 5 is a graph representing the proportions of these Mg-Fe minerals, and also the total oxides of iron, magnesium, manganese and titanium shown in Analyses 50-63. Silica, water, phosphoric acid and sulphur are not included in this graph based on our chemical analyses. A study of Figure 5 shows that in the acid portion the dark minerals determined by the microscopic method are in some cases less than the total percentage of the five oxides (FeO, Fe_2O_3, MgO, MnO, and TiO_2), which must be combined with silica and other components to form the ferro-magnesian minerals shown by Phemister. The chemical analyses, therefore, suggest a much higher proportion of dark minerals in the acid part of the intrusive. In the basic part of the eruptive the two methods are more in agreement.

It is plain from the analyses that there is a fairly rapid transition between the two facies of the eruptive, but the microscopic method indicates that it is many times more rapid than do the chemical analyses. In a large measure the same undue contrast is shown by the study of the percentages of Mg-Fe minerals and of the total bases which must be contained in them.

In the opinion of the writers, the microscopic quantitative determination of minerals in such rocks as those found in the acid part of the nickel eruptive is bound to be very tedious owing to the fineness of grain and frequent alteration of the original minerals. If the mineralogical break between the acid and basic facies were so hopelessly sudden and complete as suggested by Phemister's eleven graphs there would be something to say in support of his thesis. His departure from the proportions chemically indicated seems to be always in the direction of increasing the sharpness of the break. The transition indicated by the chemical analyses is always far more gradual.

A study of his graph for the Capreol section and a comparison of the quantitative results given in it, with the chemical data submitted herewith, show a divergence almost as great as indicated above in the Levack section.

Phemister,[1] in describing the succession of rocks in this section, says:

> About half a mile south of the northern contact of the "norite" the latter forms a steep cliff. At the foot of the cliff the first exposure beyond the talus is a very dark rock, high in ferromagnesian minerals. This basic modification gives place within 20 yards to micropegmatite in which free quartz is visible.

This stands in sharp contrast to the chemical data shown in Analyses 42 to 45, where the silica percentages for four specimens taken at approximately equal distances over a distance of a fifth of a mile are as follows: 59.34, 61.97, 64.10 and 68.92.

If the same method of quantitative mineral determination was employed for the other nine sections, the graphs will doubtless diverge equally from those based on chemical analyses.

Chemical Composition of Other Sudbury Rocks

The rocks within the syncline, around which the nickel-bearing eruptive appears in a great elliptical zone, have in the past attracted little attention. The succession of these sedimentary formations is as follows:

(*a*) Impure sandstone or graywacke.
(*b*) Black slate.
(*c*) Devitrified volcanic tuff.
(*d*) Conglomeratic phase of *c*.

Analyses made on typical specimens from each of the above are given in 75-78.

[1]Phemister, T. C., *Op. cit.*, p. 8.

CHEMICAL COMPOSITION OF OTHER SUDBURY ROCKS

	75	76	77	78	79	80	81
SiO_2	69.65	66.57	61.43	69.66	74.60	74.40	47.20
TiO_2	.39	.24	.49	.42	.24	.25	3.02
Al_2O_3	12.64	7.65	10.11	12.86	11.10	10.69	13.91
Fe_2O_3	.86	.85	3.27	1.40	.94	.94	3.28
FeO	4.08	6.62	7.15	2.40	.98	1.54	11.96
CaO	.28	1.01	3.03	1.16	1.48	.72	7.92
MgO	2.46	7.83	5.13	1.44	.76	.78	6.18
MnO	.03	.22	.21	.05	.01	.01	.42
Na_2O	3.58	.26	2.94	4.86	2.84	2.78	3.48
K_2O	2.26	.70	2.87	3.36	5.72	6.52	1.46
H_2O	2.43	3.83	2.02	1.73	.55	.89	.69
CO_2	.05	1.10	.05	.13	.37	.04	.09
P_2O_5	.17	.21	.12	.19	.05	.01	.62
S	.02	.08	.91	trace	.01	.03	.11
C	.61	2.92	.48	.....	.....	.....	.....
	99.51	100.09	100.21	99.66	99.65	99.60	100.34
O eq. of S	.01	.04	.34	.....	....	.01	.06
	99.50	100.05	99.87	99.66	99.65	99.59	100.28
S.G.	.....	.....	2.66	2.61	.....	.....	.....

75. Sandstone, Larchwood.
76. Slate, Errington Mine.
77. Tuff, C.P.R. east of Levack.
78. Conglomerate, Windy Lake.
79. Granite, 2 miles northwest of Murray Mine.
80. Granite, Murray Mine Contact.
81. Olivine Diabase, Hanmer Tp.

The three upper members of the sedimentary series are all characterized by a considerable amount of carbon. These rocks on fresh surfaces are generally dark in colour, or even black, due to the carbon, and gray on exposed weathered surfaces. The analyses indicate that the sandstone is a very impure arkose, that the slate has been formed from well leached and weathered detrital material as indicated by the high ratio of potash to soda, and magnesia to lime, and that the tuff has the composition of an intermediate igneous rock diluted with material similar to that of the slate. This last suggestion is supported by an examination of thin sections of the tuff which always shows a very fine-grained cement, which is nearly opaque, between the characteristic volcanic fragments. In the field the tuff appears to pass into the slate by the gradual reduction of the proportion of volcanic fragments.

The conglomeratic phase of the sedimentary series may be in some cases rather agglomeratic, and then related to the tuff, though at other times the boulders and pebbles are more varied. The contact surface of the pebbles with the cement is often transitional and lacking in definition. In many instances this formation has suffered so great alteration by the micropegmatite that there is an ill-defined zone of such altered rock between the conglomerate and the acid part of the eruptive. An analysis of a medium-grained conglomerate from the east side of Windy Lake is shown in 78. A critical study of this analysis shows that there has been little leaching out of lime and soda such as characterizes well-weathered sedimentary material. The relatively high lime-magnesia and soda-potash ratios suggest a rock either igneous or, if sedimentary, then formed from the consolidation of fragmental material which has not been weathered.

Later than the norite-micropegmatite intrusive is a medium-grained pink granite which forms considerable areas along the southeastern flank of the eruptive, while at times it forms breccias with the norite as seen at the Murray mine contact, and intrudes both norite and micropegmatite. Good examples of intrusion of the norite may be observed north of the Creighton mine, and on the Canadian Pacific Railway west of the Murray, while similar intrusions into the micropegmatite occur northwest of the Cameron mine. Three analyses of this younger granite have been made, 71 in the Cameron mine series where the granite intrudes micropegmatite, 79 on the railway about two miles west of the Murray where it is intrusive into norite, and 80 from the Murray mine contact intrusive into the norite. The granite which is north of the Creighton mine is of the same nature

both in the field and in thin sections. Phemister[1] regards the rock north of the Creighton as micropegmatite, and uses this conclusion to support his contention that the micropegmatite must be younger than the norite.

The last important rock type associated with the nickel-bearing rocks is a very fresh olivine diabase which forms numerous dykes with a west-north-west direction. These dykes cut all the older rock types, and may be observed in the vicinity of Sudbury and along the railway to Larchwood. Analysis 81 was made on diabase from lot 6, con. IV of Hanmer township.

The Ore Deposits

The Sudbury nickel region has been for nearly a quarter of a century the most important producer of nickel in the world. About 88 per cent. of the world's supply is now derived from this area, and recent discoveries would make it appear that the Sudbury mines will continue to hold this premier position for a long time to come, unless some remarkable discoveries of this metal are made in other regions. There is probably 150,000,000 tons of nickel ore carrying between 2 and 4 per cent. of the metal in actual reserves in this field, besides many millions of tons of probable reserves.

In addition to nickel, large quantities of copper occur in all the ore bodies, and in the lower portion of the recently developed Frood deposit the content of this metal exceeds 20 per cent. Considerable quantities of gold, silver, and members of the platinum group of metals are also recovered. The production from the field in 1928 amounted to 96,755,578 pounds nickel, 66,000,000 pounds copper, 3,850 ounces gold, 222,924 ounces silver, 10,452 ounces platinum, and 11,389 ounces palladium. The ore raised for that year was 1,457,910 tons, giving 66 pounds nickel, 41 pounds copper, 0.0026 ounces gold, 0.15 ounces silver, and 0.016 ounces of the members of the platinum group per ton of ore. The total value of the metals produced was over $32,000,000, indicating that the region is one of great economic importance. It

[1]Phemister, T. C., Ont. Dept. of Mines, vol. 34, Part 8, p. 20.

gives promise of a greatly increased annual yield, particularly in copper, precious metals, and platinum. Large quantities of zinc and lead will also be produced from new mines, such as the Errington, in the interior of the basin where the ores are of a distinctly different type from those of the nickel ranges.

(*a*) *Relations of the Ore Deposits to the Nickel Eruptive*

A glance at the geological map of the Sudbury area shows that most of the ore bodies are situated around the basic margin of the norite-micropegmatite intrusive. There are a few important deposits and a number of small ones in intrusions close to the main nickel basin, and these are regarded as offshoots of the norite of the nickel eruptive. Although the connecting links are not exposed, the intrusions consist of similar rocks, and in most respects the ores are similar.

The ore bodies on the margin of the main intrusive sheet have been classified by Coleman[1] as *marginal* deposits and those in the outlying intrusions as *offset* deposits. The marginal deposits are subdivided into two types: (*a*) Those dipping towards the axis of the basin and containing more than twice as much nickel as copper, and (*b*) faulted marginal deposits that are irregular in character, contain much rock mixed with the ore, and have a copper content equal to or even greater than that of nickel. The offset deposits are also of two types: (*a*) Columnar offsets, of great vertical extent, roughly cylindrical in form and usually richer in copper and precious metals than the marginal deposits, and (*b*) parallel offsets, sheet-like in form, dipping towards the main basin and containing ore like that in the marginal deposits.

The typical marginal deposits always have a hanging wall of norite into which the ore minerals grade without any perceptible break, the upper border of the deposit being in all cases a commercial rather than a geological boundary. The footwall shows a marked contrast to the hanging wall,

[1]Coleman, A. P., The Nickel Industry, with special reference to the Sudbury Region. Can. Dept. of Mines, Mines Branch, 1913, p. 38.

as it may be composed of a variety of rocks which in many cases show a certain amount of replacement and impregnation by sulphides, but which in some mines are little affected by them. These deposits, where they have not been affected by faulting, usually dip towards the centre of the basin at angles of 30 to 50 degrees. Such deposits may be associated in the same mine, as at the Creighton, Falconbridge and Levack mines, with offset deposits which are closely connected with the main nickel-bearing sheet. These occur where the massive sulphides have penetrated the footwall of granite, gneiss, greenstone, or quartzite, and the ore in them is practically the same as that in the adjacent marginal types.

The marginal deposits mostly occur where the bays of the norite project into the older and underlying formations and never on the recessional edge of the norite. This is regarded as an important feature when the origin of the ore deposits is considered, as the ores have settled into the depressions along the norite contact. Further, it may be observed that there are many more of these deposits where the basic portion of the nickel eruptive is relatively wide as along the southern border of the basin. In this section of the nickel field there are miles of the contact with gossan overlying ore bodies large and small, or norite spotted with sulphides. From the Gertrude mine to the Falconbridge mine near the southeastern corner of the nickel basin there are very few sections of the norite contact, except where later granite intrusions abut against the norite, in which some evidence of sulphides is not seen in brown and red gossan capping. At the Creighton mine there is a band of ore and spotted norite about three-quarters of a mile long, and the Falconbridge deposits occupy a section of the contact 11,200 feet in length.[1] On the northern range, where the norite zone is much narrower, the number of ore deposits is much smaller, and considerable sections of the contact are practically

[1]Roberts, Hugh M. and Longyear, Robert Davis, Genesis of the Sudbury Nickel-Copper Ores as Indicated by Recent Explorations. Trans. Amer. Inst. Min. Engs., 1918, p. 564.

devoid of sulphides. There are no sulphide bodies containing nickel in the main portion of the micropegmatite of the nickel eruptive, although copper, lead, and zinc sulphides occur in large quantities in faulted areas in the sediments in the interior of the nickel basin and to a small extent in the micropegmatite. These deposits are distinctly separated in character and genesis from the nickel-bearing ore bodies.

In some of the marginal deposits much faulting has occurred, and the faults have disturbed the normal relations of the ore to the walls of the ore deposits. In the Crean Hill, Garson, Falconbridge and other deposits, movements have brought masses of ore into granite, greenstone, and quartzite, and these rocks into the ore bodies, so that instead of a footwall dipping gently towards the main basin there may be found vertical contacts and very complicated relations. In addition, the fracturing has also permitted the circulation of much water, hot and cold, that has greatly changed the character of the wall rocks and ores, and introduced gangue minerals almost foreign to the typical marginal deposits.

The offset deposits present certain genetic problems much more difficult of solution than those of the marginal type. The rocks in these are, in many respects, similar to those in the basic portion of the main intrusion, but they are more difficult to identify because of their much greater alteration. The silicates in the norite adjacent to the marginal deposits are often fresh and easily identified, while many of those in the offset deposits are greatly altered, and in the Frood offset there are very few of the original ferro-magnesian minerals remaining. As a consequence the rocks in the intrusions have been identified by different writers as norite, gabbro, quartz-diorite, diabase and amphibolite. Enough can be gleaned from the information available to connect these intrusions genetically with the main sheet, and this relation has apparently been accepted by practically all investigators. There has been considerable speculation, however, as to the geological relations of the main sheet and these offset intrusions. The projection of the norite as a dike-like mass from the northern border of the eruptive to the Ross mine

suggests that the Worthington offset, about four miles in length, may be a similar intrusion with the connection near Victoria mine obscured. The Frood-Stobie, parallel offset, has been explained by Coleman as due to two possible relationships. It may be connected with the bottom of the main sheet by a subterranean connection, or it may have been connected to the main sheet above it when this sheet extended much farther southward, before erosion removed a large section of it and destroyed the connection. In this case the offset would extend downward as a sack closed at the bottom. The recent development of the Frood ore body seems to indicate that the ore body tapers down to a thin edge below the 3,000-foot level, but to what depth the igneous intrusion extends is unknown. It is probably easier to explain the conditions existing in this ore body, which is the largest yet discovered in the field, by assuming that there was a subterranean connection with the main magma than that the connection ran upward from the present surface to the intrusive sheet, although that connection is believed to have been cut off by a later granite intrusion lying between this offset and the main sheet to the north. This ore body showed signs of dipping northward toward the basin in the first 3,000 feet, but at the bottom this inclination is not pronounced.

The Copper Cliff offset is characterized by remarkable columnar ore bodies, or chimneys, of cylindrical shape and of great vertical, compared with horizontal, dimensions. They occur within the norite and stand roughly parallel to the walls of the intrusion. It is not easy to explain their origin with entire satisfaction by any of the theories advanced to account for the origin of the nickel ores.

The ores of the Sudbury area may be grouped into two major divisions: (1) nickel-copper-platinum ores, and (2) zinc-lead-copper ores. Both of these types contain varying quantities of gold and silver. The first group is confined to the basic portion of the nickel eruptive, and the second to the micropegmatite and the sediments in the interior of the basin where the deposits are related to faults and other fissures. They illustrate the principle of zoning in that the nickel-copper ores are regarded as earlier and of higher temperature deposition than the zinc-lead ores. Small quantities of lead and zinc are found in veins in a few of the nickel deposits, but they are later in all cases than the nickel ores.

The nickel-copper ores are very similar throughout the region, and they are rather monotonous mineralogically. They consist of pyrrhotite, pentlandite, chalcopyrite, and pyrite and magnetite in small quantities, the first three of these constituting by far the greater part of all the deposits. The order of deposition in practically all cases has been according to all investigators magnetite, pyrrhotite, pentlandite and chalcopyrite. Pyrite appears to precede the pyrrhotite in some deposits, and to succeed the chalcopyrite in others. A remarkable feature of the undisturbed marginal deposits is the almost entire absence of ordinary hydrothermally deposited gangue minerals—quartz and carbonates. These ores are massive sulphides with little gangue. Quartz and carbonates are fairly abundant in some of the faulted marginal deposits and in the offset deposits. Copper is higher in most of the offset deposits in proportion to nickel, and gold, silver, and the platinum metals are higher in the offset than in the marginal deposits. Lead and zinc are found also in some of the offsets, as, for example, in that on which the Worthington mine is located. Where these occur they are usually in small veins, and belong to a later stage than the nickel-copper ores.

(b) *Origin of the Ores*

There has been much controversy over the origin of the ore deposits in this region. Geologists have divided mainly on two theories: the magmatic and the hydrothermal. Those like Barlow,[1] Coleman,[2] and Roberts and Longyear,[3]

[1]Barlow, A. E., Geol. Surv. Can., Vol. XIV, Part H, 1901.

[2]Coleman, A. P., The Sudbury Nickel Field. Ont. Bur. of Mines, Vol. XIV, Part III, 1905. The Nickel Industry with special reference to the Sudbury Region, Can. Dept. of Mines, Mines Branch, 1913.

[3]Roberts, Hugh M., and Longyear, Robert Davis, Genesis of the Sudbury Nickel-Copper Ores as Indicated by Recent Explorations. Amer. Inst. Min. Engs., 1918.

who have done most field work in the area, have strongly supported the magmatic theory, while those who have studied carefully the ores in the laboratory or worked in restricted portions of the field have been almost equally strong supporters of a hydrothermal origin. Among the latter are Dickson,[1] Campbell[2] and Knight,[3] Tolman and Rogers,[4] Wandke and Hoffman,[5] and Phemister,[6] as well as many others. A large number of other geologists have supported the magmatic theory, while a few, such as Howe[7] and Bateman,[8] have held views which may be regarded as a compromise between the two theories mentioned. Bateman has advocated differentiation in the magmatic reservoir at greater depth than the present position of most of the ore deposits and the injection of the sulphides in the molten condition as massive bodies into the offset and some of the marginal deposits.

The arguments for direct differentiation from the norite are based on the close association of the ores everywhere with the norite. There is no nickel ore where there is no norite or related basic rock. The differentiation in place of the sheet, as a whole, into a basic phase and an acid micropegmatitic phase, as demonstrated in preceding sections of this article, is an indication of the extent to which differentiation has been carried *in situ*. It strongly supports the argument that the sulphides also differentiated from the sill

[1]Dickson, C. W., The Ore Deposits of Sudbury, Ont., Trans., Amer. Inst. Min. Engs., vol. 34, 1903.

[2]Campbell, W. C. and Knight, C. W., On the Microstructure of Nickeliferous Pyrrhotites, Econ. Geol., vol. 2, 1907.

[3]Knight, C. W., Royal Ont. Nickel Commission, 1917.

[4]Tolman, C. F., Jr., and Rogers, A. F., A Study of the Magmatic Sulphide Ores, Leland Stanford Junior University Publications, 1916.

[5]Wandke, Alfred and Hoffman, Robert, A Study of the Sudbury Ore Deposits. Econ. Geol., Vol. 19, 1924.

[6]Phemister, T. C., Igneous Rocks of Sudbury and their Relation to the Ore Deposits, Ont. Dept. of Mines, vol. 34, Part 8, 1925.

[7]Howe, Ernest, Petrographical Notes on the Sudbury Nickel Deposits, Econ. Geol. ,vol. 9, 1914.

[8]Bateman, Alan M., Magmatic Ore Deposits, Sudbury, Ont. Econ. Geol., vol. 12, 1917.

itself by the action of gravity on an immiscible silicate-sulphide melt. The association of nickel-copper ores in Norway, and of nickel-copper-platinum ores in South Africa, with similar basic rocks and their differentiates is in favour of the magmatic theory and opposed to that of hydrothermal origin. The occurrence of most of the marginal deposits of the Sudbury region in bays of the norite in the older rocks beneath indicates a settling of the heavier sulphides into these depressions, while there is little ore on the projections of these rocks into the norite.

Probably the strongest arguments for the direct differentiation of the sulphides from the norite in place are the very fresh condition of the silicates in contact with the sulphides in the unfaulted marginal deposits and the gradation from massive sulphide ore to pyrrhotite-norite spotted with sulphides. This spotted norite extends hundreds of yards from the contact of the sheet. Magnetite, a constituent of the sulphide ore, is found almost everywhere in the norite intergrown with biotite, and sulphides are found intergrown with biotite, hypersthene, and feldspar, which are often perfectly fresh, in such a way as could not possibly exist if they had been introduced by hot waters (Plate II). In some cases the most delicate crystals have not been altered in the least by the formation of the sulphides, and hypersthene, which is an easily altered mineral, is quite fresh in the spotted norite. The quantity of sulphides in portions of the norite is very large, and this feature cannot be ignored in any consideration of the problem of genesis. For example, Wandke and Hoffman[1] have stated that at the Creighton mine there is a band three-quarters of a mile long and 600 yards wide spotted with sulphides. Two analyses of the spotted norite overlying the Creighton deposit have been made by Culbert and Haller, and they show 1.56 and 0.69 per cent. sulphur. The average of these analyses is 1.12 per cent., equivalent to 2.83 per cent. when calculated as pyrrhotite or 3 per cent. when calculated as half pyrrhotite and

[1]Wandke, Alfred and Hoffman, Robert, A Study of the Sudbury Ore Deposits, Econ. Geol., vol. 19, p. 200, 1924.

half chalcopyrite. Even if it be assumed, in accord with Wandke and Hoffman, that on an average only one-half of one per cent. of this rock is sulphides, it will be found that for each 1,000 feet in depth the rock will yield 3,175,200 tons of pure sulphides. The mine has yielded, to the end of 1928, 12,953,964 tons of sorted ore (containing 20 to 25 per cent. rock) to a depth of 2,700 feet,[1] or about 4,800 tons per foot. This gives 4,800,000 tons of ore per thousand feet, which is not much in excess of the sulphides in the spotted norite.

The following are arguments advanced in favour of hydrothermal origin of the ore deposits. Microscopic study of the ores shows that sometimes there has been much replacement of silicates by sulphides and of one sulphide by another. Much stress has been laid upon the order of deposition of sulphides—pyrrhotite, pentlandite, and chalcopyrite—as indicating deposition from hot waters rather than by crystallization from a magma. A recent investigation of pyrrhotite-pentlandite melts by Newhouse throws important light on this phase of the problem. He found that the relations between pyrrhotite and pentlandite observed in these melts were the same, with one exception, as those in the natural ores of Sudbury and Alexo, Ontario, Lancaster Gap, Pennsylvania, and Dalton, Massachusetts. He further states that these relations are not those found in the hydrothermally deposited minerals such as are found in veins.[2] This seems to offset quite effectively the reasons advanced by Dickson, Campbell and Knight, and Tolman and Rogers for a hydrothermal origin of the nickel-copper ores as a result of their mineralographic studies.

The presence of granite intrusions later than the norite in the vicinity of several of the ore bodies has been advanced by some geologists as a strong indication of the close relationship of the ores with these rocks. On the other hand, there is a much closer relation between the norite and the ores as

[1]Collins, E. A., International Nickel Company of Canada, Personal communication.

[2]Newhouse, W. H., The Equilibrium Diagram of Pyrrhotite and Pentlandite and their Relations in Natural Occurrences. Econ. Geol., vol. 22, 1927.

there are many deposits which are not in any way associated with these granites. If the ores came in with the granites, why did they impregnate the norite for hundreds of yards from the contact, and at the same time affect the footwall rocks relatively to so small an extent?

In many of the deposits the sulphides fill cracks in brecciated norite and rocks of the footwall, suggesting that they are distinctly later than the norite. Some of the ore bodies in the Creighton, Falconbridge, and Levack deposits are found in the granite and other rocks of the footwall. This is also regarded as an indication of a source other than the norite. However, all these relations can be readily explained by the magmatic segregation theory if it be borne in mind that large quantities of the sulphides were probably liquid, mobile, and under great hydrostatic pressure, so that they could traverse any line of weakness which occurred, and that it was almost as easy for them as for solutions from greater depth to enter the footwall. These bodies of sulphide may be regarded as moving considerable distances in some cases. The filling of fractures in the brecciated norite along the contact is also possible when it is considered that several geologists have recognized that the lower portion of the nickel eruptive was chilled against its floor before extensive differentiation occurred, and that this lower portion was undoubtedly fractured during movements which took place around the border of the sill before the whole was consolidated. Evidence of these movements is found in many of the mines, and they account for the injection of much of the hydrothermal gangue minerals found in these disturbed deposits.

The offset deposits offer some problems not met in considering the origin of the marginal types. They invariably show much more evidence of hydrothermal action than the others, in the greater alteration of the norite, more replacement of wall rocks and of one sulphide by another and also in the larger ratio of copper and precious metals to nickel. In parts of these deposits the nickel-copper ores are similar to those in the main nickel range and they occur with similar

rocks, but there has been much sorting of the sulphides and probably the addition of considerable copper and metals other than nickel. The Frood ore body with over 110,000,000 tons of proven ore and one of the richest ever discovered is a great sheet-like mass part of which consists of copper-nickel ore, which is very similar to that in the marginal deposits. In the upper levels there is much low grade ore and basic to intermediate rock spotted with sulphides. At lower levels the copper to nickel ratio increases greatly until it reaches a ratio of about 21 of copper to 1.7 of nickel below the 3,000-foot level where the ore body is practically solid sulphides.[1] The platinum and precious metals also increase out of proportion to the base metals. In such a deposit the quantity of associated norite is apparently too small to supply such a great mass of copper ore without additions from some outside source, and additional copper was probably added to the intrusion from the main magma as liquid sulphides and by hydrothermal solutions. Corless has stated that copper has an atomic weight about 8 per cent. greater than that of nickel and 14 per cent. higher than that of iron, although chalcopyrite has a density 9 per cent. less than pentlandite or pyrrhotite. He raises the question whether in the liquid state these relations may not have been different, thus permitting the copper sulphide to settle to the bottom in large proportions, leaving the more rocky ore floating in the upper part of the intrusion.

In the interior of the nickel basin, where sediments overlie the micropegmatite, large deposits of zinc-lead ores, carrying considerable copper and some precious metals have been discovered. These differ in character from the nickel ores associated with the norite in their composition, their relations to faults which cut the nickel eruptive, and the absence of any direct relation to norite. They are later in age than the main nickel deposits, and have every appearance of being hydrothermal replacement deposits formed during the latest stages of the cooling of the nickel eruptive.

[1]Corless, C. V., The Frood Ore Deposit, A Suggestion as to its Origin. Can. Min. and Met. Bull., March, 1929.

CONCLUSIONS

The more important points in the foregoing paper may be briefly noted in conclusion as bearing on the question of magmatic segregation.

The field study of several sections across the eruptive sheet has been supplemented by the determination of specific gravity of hand specimens, by the study of many thin sections with the microscope, and by the making of a large number of rock analyses, and there can be no doubt that the eruptive sheet is a unit formed by the segregation of a magma into a more basic portion, norite, passing without a break upwards into a more acid phase, micropegmatite. There is, however, a tendency for the lower and upper edges, where cooling began, to be a little nearer the average in composition than the parts adjacent, which had a longer time for magmatic segregation.

The excellent series of analyses of rock specimens collected during four traverses across the whole width of the eruptive sheet deserve particular mention, as giving a far more complete knowledge of the composition of the rock with which the Sudbury ores are associated than was available previously. It is doubtful if any other case of magmatic segregation has been so carefully investigated from the chemical side, and thanks are due to the gentlemen who have carried out the analyses.

In the lowest parts of the eruptive sheet, sulphides (pyrrhotite, pentlandite, and chalcopyrite) occur as blebs scattered through the norite in such a way that they must have been present when the magma cooled. When they occur in large numbers, the rock, pyrrhotite-norite results, and this is found at every ore deposit. In marginal mines the ore passes gradually into pyrrhotite-norite and the upper limit of workable ore is determined by assay.

The rock enclosing these blebs of ore is often perfectly fresh, the minerals showing no sign of disturbance since they crystallized in cooling, showing that this part of the sulphides is of magmatic origin.

There is a marked relation between the width of the eruptive sheet and the amount of ore in the deposits, narrow parts and inward bends of the norite edge having no ore, while outward bays at broad parts provide large ore bodies. The Falconbridge nickel deposit, though entirely hidden by drift, was foretold by this law and was discovered later by diamond drilling.

While norite always accompanies the ore, other country rocks do not affect it in any way. The foot wall at one mine or another consists of granite, gneiss, greenstone, graywacke, or quartzite, yet the ores of all the mines consist of the same three sulphides, as monotonous as the norite which everywhere accompanies them.

In unfaulted marginal deposits there is usually no evidence of rearrangement of the materials by the action of water; but in most offset deposits hydrothermal effects are to be seen; and in the smaller ones at a distance from the norite edge there is often much rearrangement of the ores, and gangue minerals, such as quartz and calcite, are found.

Conditions are different in the lead, zinc, and copper deposits of the interior basin, which were formed entirely by hot solutions coming from the acid edge of the eruptive and show no signs of a directly magmatic origin.

The statements just made respecting the norite-micropegmatite sheet and its relations to the nickel-copper ores at or near the basic edge are not speculative, but are proved facts recognized by all the geologists who have done the work of mapping the region. No theory of the formation of the ore deposits which does not account for all of them can be correct, and the theory of magmatic segregation is the only one which does so. That there were modifications of offset deposits by circulating waters derived from the parent magma is accepted by all students of the mining region and fits in perfectly as an after effect in the magmatic theory.

On the other hand, the hydrothermal theory fails completely to account for the relations shown above, particularly in regard to the immense amounts of sulphides enclosed in the pyrrhotite-norite, in which the rock shows no sign of attack by hot solutions.

The only possible source of the great ore deposits which encircle the norite-micropegmatite basin is the eruptive mass itself, with which they are all connected, and even hydrothermalists must admit that the sulphides were in some way derived from it. It is an absolutely proved fact that small masses of sulphides of exactly the same kind occur completely enclosed in fresh norite, with no hint of an opening through which water could circulate. Until the hydrothermalists have accounted for them, they have not solved the problem of origin. They are studying secondary changes in the ores, and overlooking the only possible origin of the ores which have undergone the changes.

EXPLANATION OF PLATES

PLATE I

Fig. 1.—Norite (Analysis 66) from Cameron Mine section. Shows idiomorphic hypersthene, plagioclase and in the centre of the picture between the feldspar crystals xenomorphic quartz (×25).

Fig. 2.—Same with + nicols shows order of crystallization to be hypersthene, plagioclase and quartz.

Fig. 3.—Micropegmatite from the Levack section (Analysis 63). The intergrowth radiates from a plagioclase crystal and with the extinction of part of the plagioclase, part of the feldspar in the intergrowth extinguishes (×25).

PLATE II

Fig. 1.—From section of norite taken near the Creighton mine showing magnetite (black) intergrown with biotite (dark grey). ×50.

Fig. 2.—From spotted norite near Creighton mine showing pyrrhotite (black) intergrown with biotite with perfectly sharp borders. ×200.

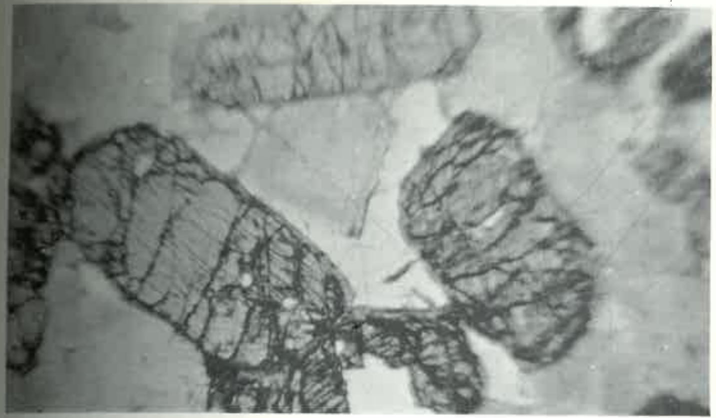


Fig. 1

Fig. 2

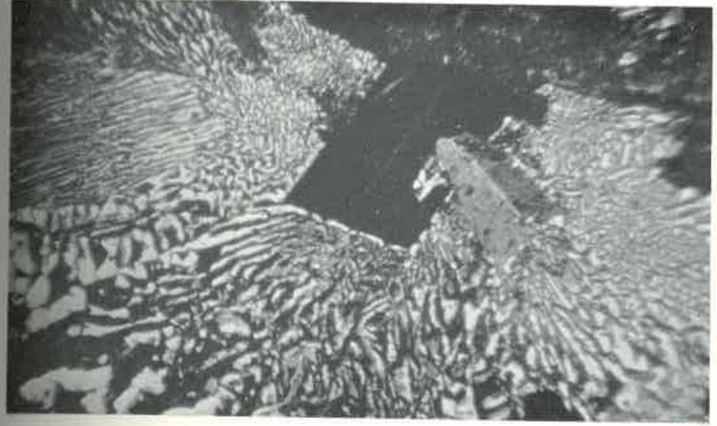


Fig. 3

Fig. 1

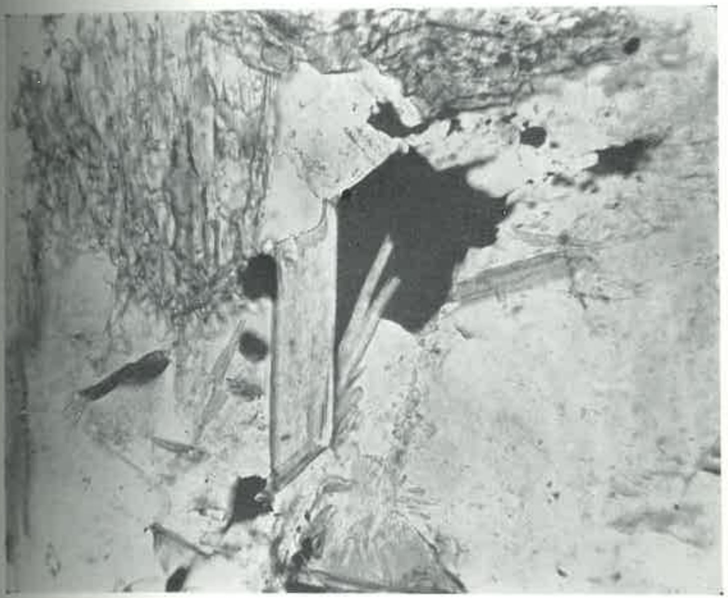
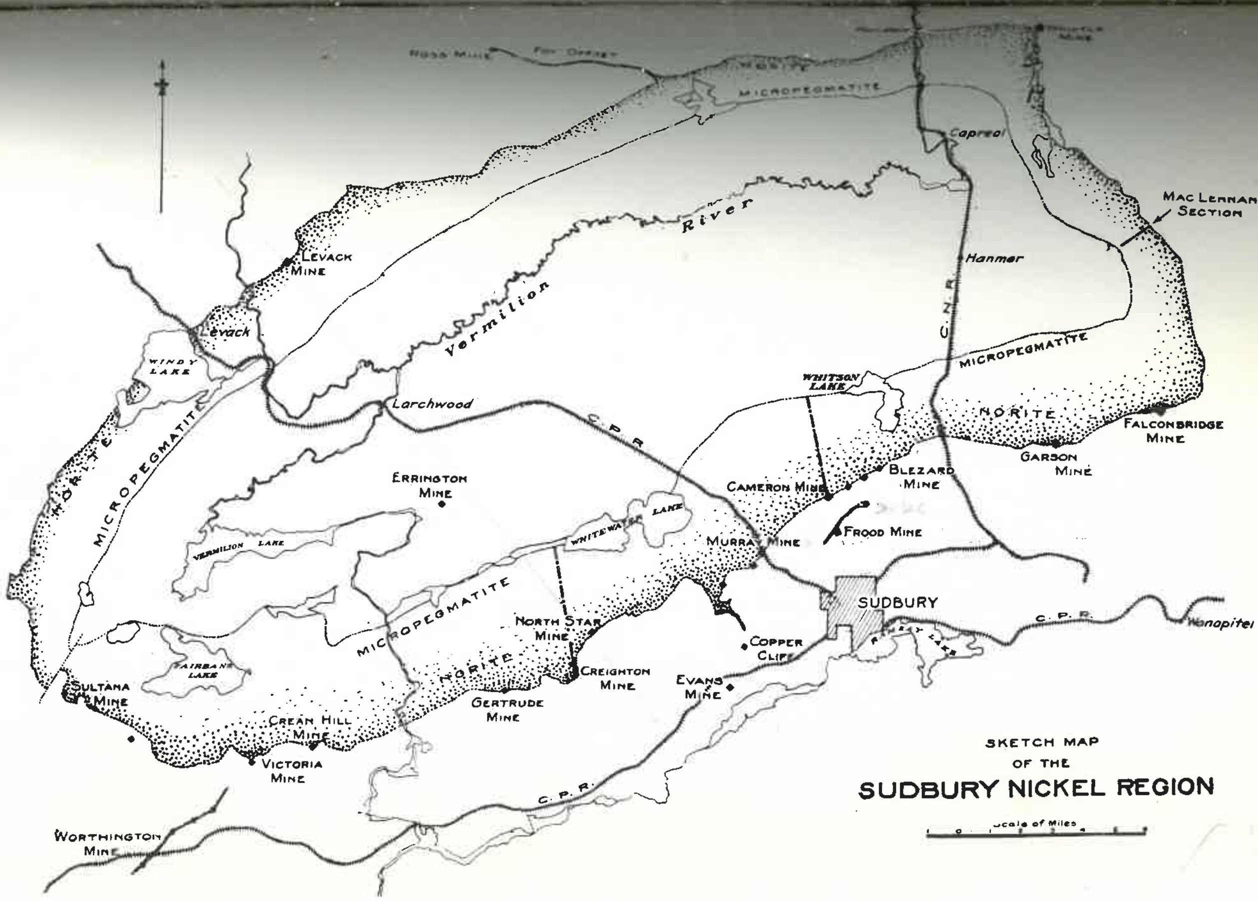


Fig. 2



SKETCH MAP
OF THE
SUDBURY NICKEL REGION