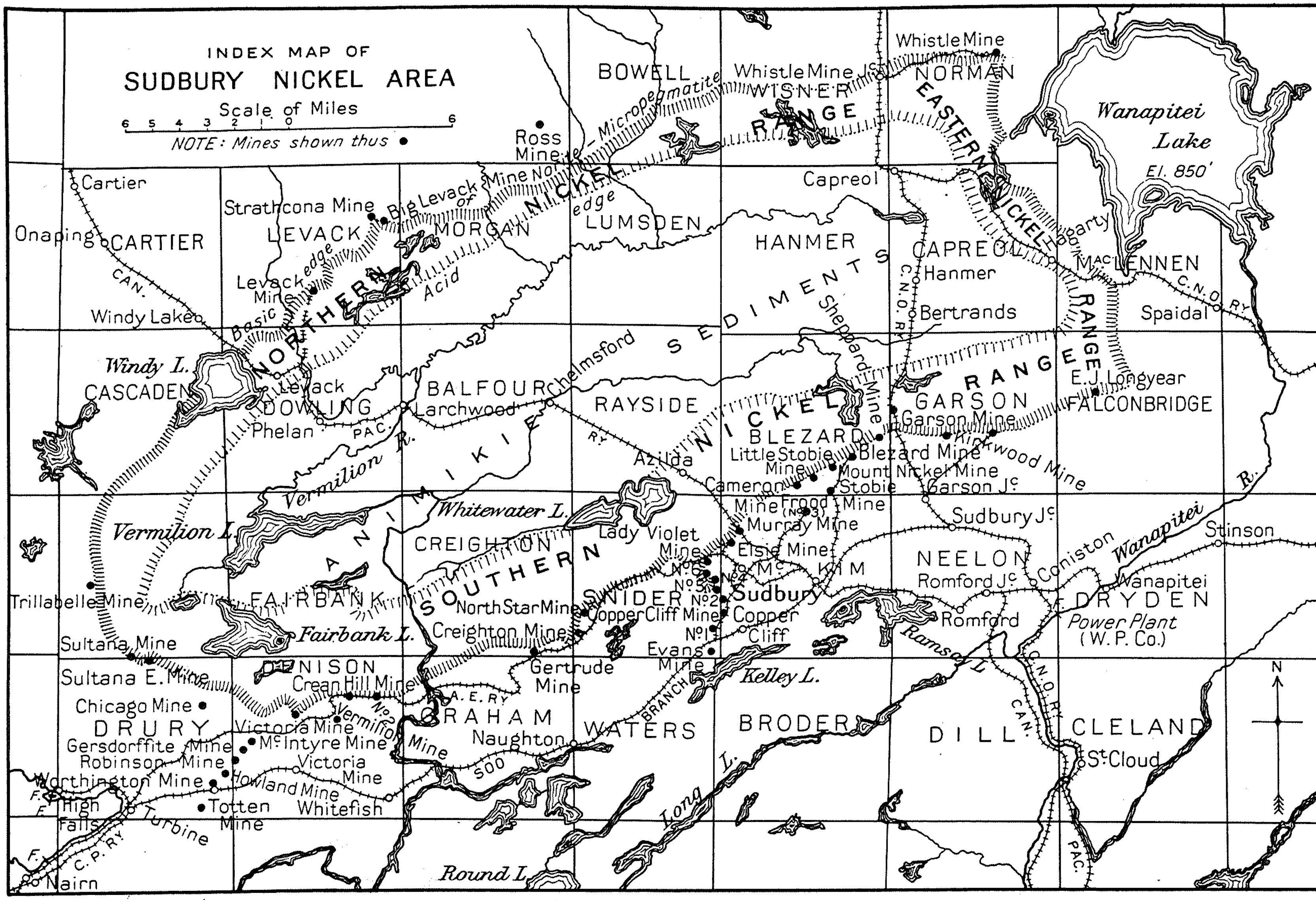

Map of the Sudbury Nickel-Copper area, Ontario, Canada, showing the location of the mines. The outlines of the norite-micropegmatite are also indicated.

(From the Report of the Ontario Nickel Commission)

GEOLOGY OF THE SUDBURY BASIN AREA
ONTARIO CANADA

by

VICTOR CLAUSON

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ABSTRACT

For many years the genesis of the Sudbury copper-nickel ores and the petrogenesis of the norite, transition zone, and micropegmatite have been the subjects of numerous published articles and reports by geologists. The recognition of the sequence of pertinent geologic events has definitely disproved the theory of magmatic segregation, in situ, of the ores from the Sudbury intrusive.

That the micropegmatite is the result of some unexplained process of magmatic differentiation from the norite, is still the consensus of geologic opinion. In a study of several hundred thin-sections of specimens of the Sudbury micropegmatite, collected from many different places, the writer has been unable to find textures that are suggestive of primary crystallization, in the micrographic intergrowths, which constitute up to 75 per cent of the micropegmatite. The textures of the micrographic intergrowths, which are composed of quartz and a wide range of feldspars, suggest that these are secondary and that they were formed by the process of metasomatism.

GEOLOGY OF THE SUDBURY BASIN AREA
ONTARIO CANADA

I
INTRODUCTION

The first discovery of ore in the Sudbury area was made in 1883, and in 1890 Robert Bell (4) first published a description of the ore deposits. Although the geology of this area has been studied for nearly sixty years, there still exist many problems, the solution of which requires much additional field and laboratory work. The geologic history of this district has been made complex by the effects of tectonic, plutonic, volcanic, and metamorphic processes, and the interpretation of some of these effects remains controversial.

For many years the genesis of these ores has been the subject for lengthy and heated arguments, and the literature on this subject is voluminous. However, sufficient evidence has now been found to disprove the theory of magmatic segregation in situ.

Although most of the field and petrographic studies applied to the Sudbury intrusive have been devoted to the norite, it has been the consensus of opinion that the micrographic intergrowth of quartz and feldspar, which constitutes an important part of the micropegmatite, is the result of primary crystallization from the magma. In this thesis the writer offers evidence to support his belief that these microtextures are the result of later and secondary processes.

The Writer's Field Experience in the Sudbury Area

The writer spent thirteen years in the Sudbury area in charge of all exploration, development, mining, and metallurgical operations in Eastern Canada for the Treadwell Yukon Corporation, Limited. During this period he frequently visited the principal copper-nickel mines in this district for the purpose of studying and discussing with the resident engineers and geologists the problems relating to the genesis of these ore deposits. During the past four years a total of twenty-eight weeks were devoted to field work in this area, and through the courtesy of the management of the International

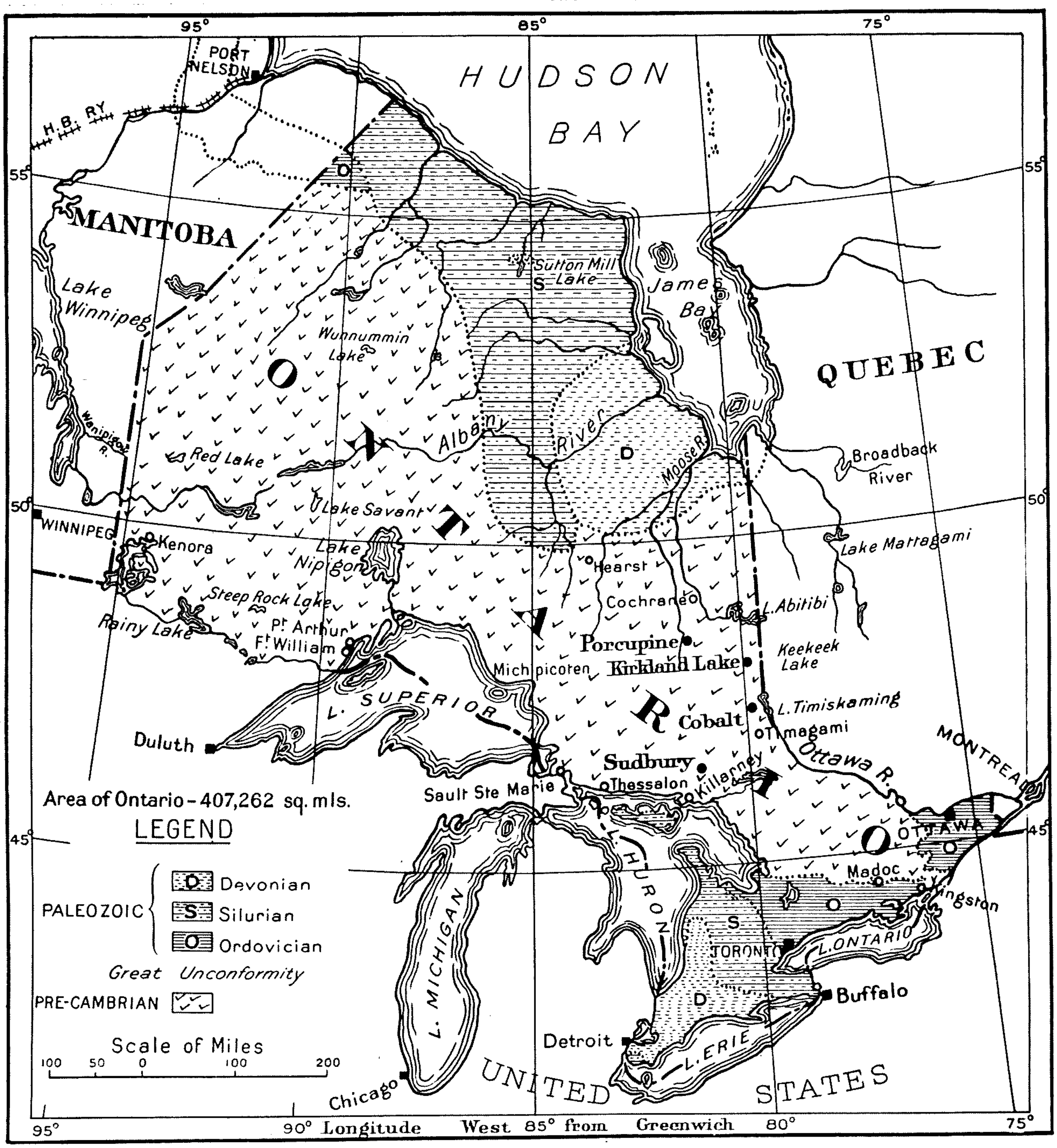
Nickel Company, the facilities of this company's research laboratories were extended to him and the voluminous data that have been collected and compiled by the geological staff were made available to him. More than 1,000 thin sections were made in the university laboratory of rocks collected in the Sudbury area; most of these were made by the writer.

Location

Sudbury, Ontario, the chief municipality of the Sudbury district, is situated about 38 miles north of Georgian Bay, Lake Huron. It is a division point on the main line of the Canadian Pacific Railway between Montreal and Vancouver, about 440 miles west of the former city. The principal mines in this area are situated west, northwest, north, and northeast of Sudbury; the distances range from two to twenty-two miles.

Topography

The most prominent topographic feature of this area is known as the Sudbury Basin, which has a length of about 37 miles from northeast to southwest and a maximum width of about



Geological Map of Province of Ontario, Canada, showing location of the Sudbury Area.

FIG. 1.

(From the Report of the Ontario Nickel Commission)

17 miles. The depressed part of this basin is enclosed by a rim of rocks having an average elevation of about 200 feet above the bottom land and a maximum elevation of 400 feet greater than the average. In the central part of the basin is a series of low disconnected ridges of sandstone which is entirely surrounded by relatively flat farmland composed of sand, silt, and clay. Slate, which underlies the sandstone, is exposed in only a few places. The inside of the rim of the basin consists of a series of volcanic rocks that range from a fine-grained tuff at the contact with the slate to coarse fragmental rocks next to a micropegmatite which forms the upper part of a composite norite-micropegmatite mass known as the Sudbury Intrusive.

History

The presence of magnetic ore in this area was first indicated in 1856 when A. P. Salter (23), provincial land surveyor, observed and reported abnormal variations in compass readings near the present site of the Creighton mine. During the same season he described his observations to Alexander Murray (28), who was engaged in geological studies in the same area for the Geological Survey of Canada. The latter collected some specimens from the magnetic locality and reported that these contained magnetic and titaniferous iron ores, copper and nickel sulphides, and magnetic and non-magnetic iron sulphides. These early reports caused no special interest in the mineral possibilities of the area, and it was not until 1883 that the first orebody of copper-nickel ore was found. This discovery was made, on the outcrop of the deposit now known as the Murray mine, while clearing the right-of-way for the Canadian Pacific Railway (41).

Most of the known deposits were found in the next four years; the following is a list of the most important of these discoveries and their locations:

Name	Concession Number	Township
Creighton	I	Snider
Frood	VI	McKim
Levack	II and IV	Levack
Whistle	IV and V	Norman
No. 4	IV	Snider
Worthington	II	Drury
No. 2	III	McKim
Copper Cliff	II	McKim
Mt. Nickel	II	Blezard
Stobie	I	Blezard
Crean Hill	V	Denison
Evans	I	Snider
Victoria	IV and V	Denison
Vermillion	IV	Denison
Chicago	V	Drury
Gersdorffite	III	Denison
Sultana	I	Trill
Kirkwood	III	Garson
North Star	III	Snider

The early prospectors observed that most of the gossans were found near the base of the norite, and that these oxidized surfaces were indicators of orebodies. The largest gossans were found on the Frood and Creighton properties; these two properties have been the largest producers and contain the greater part of the developed ore reserves of the district.

In 1887 a shipment of ore from the Copper Cliff mine was sent to the Orford Copper Company's plant at Constable Hook, New Jersey. Difficulty was experienced in smelting this lot, and it was then that nickel was first recognized as an important constituent of these ores (41).

The mineral sperrylite (PtAs) was first discovered in a shipment of ore from the Vermillion mine by F. L. Sperry, chemist for the Canadian Copper Company. This mine was first operated for the gold content, and one shipment of about 200 tons of ore, taken from the gossan, assayed 4 ounces silver, 4 ounces palladium, 1.5 ounces platinum, and 0.33 ounces gold (10).

In 1897 T. L. Walker (48) stated that the Sudbury intrusive is composed of two varieties of rock which he considered to be the result of gravitative differentiation during the cooling of the original magma. He was the first geologist to suggest that there was a regular composition gradient upward from the norite, containing about 50 per cent silica, to a micropegmatitic granite containing about 70 per cent silica. He also adopted the suggestion made by Bell (4) that: "If the diorite (norite) flowed out originally upon the nearly horizontal surface of the other rocks, the constituents of the ore which it contained may have sought the lower portions of the mass." During the next several years Barlow (2) developed the theory of gravitative differentiation for both the Sudbury intrusive and the ores. After three years of study, Coleman (14) became the principal exponent of this theory and continued to support this concept for the remainder of his life (11).

Harker (30) was the first geologist to question the above theory of Walker, Barlow, and Coleman as applied to the Sudbury intrusive. He found no indication of a regular "composition gradient" in either the norite or the granophyre (micropegmatite) considered separately, and he considered the transitional zone to consist of a characteristic hybrid rock. Knight (35, 36) collected specimens at short intervals across several sections of the intrusive and had these chemically analyzed. These analyses proved that there is not a regular gradation from the norite to the micropegmatite. Phemister (42) collected specimens across eleven sections of the intrusive and made Rosiwall analyses of these specimens. These prove that the most basic portion of the intrusive is found near the top of the norite and not at the basal contact, and that a comparatively narrow transition zone occurs between the norite and micropegmatite. Phemister concluded that the Sudbury intrusive is not a single intrusion, but two.

During the period of 1928-1932, W. H. Collins (18) with several assistants made a detailed study of the Sudbury area and re-mapped the Sudbury intrusive and the "offsets." Collins concluded that the result of their work is essentially a confirmation of the opinions and conclusions that had been expressed by Walker, Barlow, and Coleman.

Since 1931 the International Nickel Company of Canada has employed a large staff of skilled geologists under the direction of Dr. A. B. Yates, with Dr. L. C. Graton as consultant. Some of the results of their work has been published (32, 33, 51).

Importance of the Area as a Source of Nickel and as a Field for the Study of Petrogenesis and Structural Features Affecting Ore Deposition

Owing to the development in the Sudbury area of the world's most important nickel deposits, this district has, for many years, been of special interest to geologists. The investigations of this area by geologists from many different schools have resulted in much controversy regarding the petrogenesis of some of the rock formations, the mechanism of emplacement of the ore, and the structural features affecting the localization of the ore.

Most of the area is covered by Pleistocene glacial and lacustrine deposits, and vegetation ranging from moss and shrubs to second-growth timber. This has limited the study of the surface areas to natural exposures and to highway and railway cuts. The application of geophysical methods, by mining companies in the area, has yielded much valuable information; but the rock exposed in the many miles of underground workings and in diamond drilling offer the best opportunities for the study of the important controversial problems for which this area is noted.

II

GENERAL GEOLOGY AND STRATIGRAPHY OF THE SUDBURY AREA

Brief Review of Pertinent Pre-Cambrian Geology

In studying the literature on this subject one finds that there is almost a universal agreement that this area includes rocks of all subdivisions of the pre-Cambrian except the Middle Huronian; but there is a general lack of agreement in classification, correlation, and nomenclature as applied to the various formations, and in the time sequence of some of the intrusives. The field relations of some of the rocks in this area are often obscure and difficult to interpret. The following Table 1 is made up from the latest records of the International Nickel Company. Table 2, compiled by Cooke (22) illustrates the lack of agreement, among the principal workers in the area, regarding the correlation of the age relations of the Sudbury and Bruce series. Table 3 represents Cooke's conception of the post-Bruce geological events in this area.

TABLE 1

TABLE OF FORMATIONS AFTER INTERNATIONAL NICKEL COMPANY STAFF 1945

Pleistocene	Boulder clay, sandy till, and lacustrine sand and clay	
Post-Keweenawan	Late faulting and shearing Olivine diabase dikes Large trap dikes Shearing	
	Quartz diorite) Breccias)	Age relations between these are still controversial.
	Small trap and aplite dikes Murray and some Creighton Granite	
Keweenawan	Micropegmatite) Transition zone) Norite)	Sudbury Intrusive
	Gabbro and other basic intrusives	
Upper-Huronian (Animikie)	Intrusive Contacts	
	Chelmsford Sandstone (grit) Onwatin Slate Onaping Tuff Trout Lake Agglomerate	Not known definitely outside Sudbury Basin. Pre-norite, but age otherwise uncertain.
Middle-Huronian		Missing from the Sudbury area
Lower Huronian (Bruce)	Serpent Quartzite Espanola Formation Bruce Conglomerate Mississagi Quartzite Ramsay Lake Conglomerate	
	Great Unconformity Not visible in Sudbury area and denied by Burrows and Rickaby, but theoretically necessary and reported by Collins from west of Sudbury	
Pre-Huronian Algoman (?)	Clarabelle Granite	Coarse uniform granite, post-Snider, pre-norite
Sudburian Timiskaming	Intrusive Contacts McKim Graywacke Copper Cliff Rhyolite Frood sub-series	
Keewatin	Elsie Mountain Greenstone Snider Series	

TABLE 2

CORRELATION OF THE AGE RELATIONS OF THE SUDBURY AND BRUCE SERIES

Fairbairn	Collins	Coleman	Burrows and Rickaby	Int. Nickel Geol. Staff	Lawson	Cooke
Lower Huronian	Lower Huronian	Lower Huronian	Timiskaming	Lower Huronian	Lower Huronian	Lower Huronian
Sudbury-Bruce Series: Serpent Espanola Bruce Mississagi Ramsay Lake McKim Copper Cliff	Bruce Series Serpent Espanola Bruce Mississagi Ramsay Lake	Ramsay Lake	Sudbury Series: Wanapitei Ramsay Lake McKim Copper Cliff Greenstone-Sediment Complex	Bruce Series: Mississagi Ramsay Lake	(Formations not definitely classed as Sudbury or Bruce) McKim Ramsay Lake	Bruce Series: Mississagi Ramsay Lake McKim Copper Cliff
Fault	Unconformity	Unconformity		Unconformity	Unconformity	Great Fault
Pre-Huronian	Pre-Huronian	Pre-Huronian		Pre-Huronian	Mississagi	Archean
Sediments and Volcanic schists	Sudbury Series: McKim Keewatin Series: Copper Cliff Volcanic schists and sediments	Sudbury Series: Wanapitei McKim Copper Cliff Keewatin Series: Volcanic schists and sediments		Sudbury Series: McKim Copper Cliff Volcanic schists and sediments Keewatin Series: Sediments and schists	(Remainder of section not studied)	Stobie Series: Metamorphosed lavas and sediments

*Compiled by Cooke (22).

TABLE 3

PRE-CAMBRIAN CORRELATIONS INDICATED FROM RECENT WORK AT SUDBURY ONTARIO*

Intrusion	Olivine gabbro dykes
Intrusion	Murray, Creighton, and probably Killarney granite
Gentle folding	Whitewater syncline
Intrusion	Norite-micropegmatite
Deposition	Whitewater lavas and sediments
Erosion	30,000 to 40,000 feet of sediments and intrusives
Probable intrusion	Birch Lake granite
Close folding	
Intrusion	Nipissing gabbro
Deposition	Cobalt series
Erosional unconformity	17,000 feet or more of sediments removed
Deposition	Bruce series

*H. C. Cooke (22)

Structure and Tectonic History of the Sudbury Area

The difficulty of correctly interpreting the tectonic history of the early pre-Cambrian rocks in this area is seen in Table 2, which shows the difference of opinions of competent geologists regarding the correlation of the Sudbury and Bruce series. The evidence of intense folding and faulting of the rocks, south of Sudbury basin, can be seen in their exposed sections. The dips of many of these sediments and volcanics are nearly vertical, and the evidence seen in cross bedding, flow tops, and pillow structures prove that some of these measures have been overturned.

Most geologists accept the theory that the Sudbury intrusive was emplaced as a sill (Coleman) or lopolith (Grout) between a maturely eroded surface of steeply tilted pre-Upper Huronian rocks and the less folded Whitewater series, which has been classified as Upper Huronian. Some of the mine workings have now reached a depth of more than a mile. The fact that there has been no flattening of the dip of the contact between the norite and the older footwall rocks has led the writer to believe that the Sudbury intrusive has the shape of an irregular funnel and represents the form of an ethmolith (46).

A number of faults are shown on the accompanying geological map of the district. The Creighton and Worthington faults are two principal east-west structures, with nearly vertical attitudes, and appear to be of the strike-slip variety. The apparent horizontal displacement of the former is 2,000 to 3,000 feet, and that of the latter 7,000 feet. The fact that trap dikes, intruded along these two faults, are generally brecciated, indicates that these movements extended over a considerable length of time.

In the southwestern part of the basin several reverse faults dipping 50 to 60 degrees southeast and striking in a northeasterly direction, offset the edge of the nickel intrusive. The largest of these are the Cameron Creek, Sultana, Victoria, and Fairbanks Lake faults. The Cameron Creek shows displacements of 12,000 feet horizontally and 3,900 feet vertically. A horizontal displacement of 6,000 feet has been measured on the Fairbanks Lake fault. The separate identities of these faults can not be traced across the interior of the basin, but continuations of some of them are seen in the faults and shear zones, in the tuff and slate, in which several copper-zinc-lead deposits have been developed.

On the north half of the basin Collins (18, Vol. 29) discovered a series of faults that strike nearly north-south, and appear to have vertical or very steep dips. The horizontal displacements of the Sudbury intrusive, along these faults, are 2,700, 2,000, 1,650, 800, and 400 feet. He also mapped a number of faults on the eastern side of the basin; along one of these horizontal displacements of the Sudbury intrusive, of

500 feet and 300 feet respectively, of the outer edge and the transition zone were measured.

In addition to faulting, Collins called attention to the prevalence of slicing which, in the aerial photographs of the area, appear as delicate, closely spaced parallel lines, resembling those of a thinly-bedded sedimentary formation. Folding, faulting, and shearing is seen throughout the members of the Whitewater series within the basin.

Immediate Pre-Cambrian Stratigraphy

Keewatin

Snider Series. The main body of the Snider series, 2½ miles long and 1 mile wide, occurs in the southern part of Snider township. It is composed of arkosic quartzites interbedded with basic volcanic flows which have been strongly folded or brecciated and, in places, intensely granitized. Yates (51) considered this to be the oldest unit of the Keewatin in this area, but later work by Michener (38) suggests that the Snider series may be a part of the Elsie Mountain-Frood series of greenstones and sediments.

Elsie Mountain Series. This series is composed principally of basaltic and andesitic greenstones, gabbro and amphibolite, a small amount of quartzite, and a minor amount of agglomerate. These rocks lie along the south contact of the norite except, for several miles along the central portion, where they are separated from the norite by the Creighton and Murray granite masses. The thickness of this series varies from one-half to two miles, the general strike is northeast-southwest, and, due to overturn, the dip is steeply to the northwest.

Sudburian (Timiskamian)

Lying stratigraphically above, but structurally below, the Keewatin series is a thick series of volcanic and sedimentary rocks which Coleman termed the Sudbury series. This has been divided into three sub-series.

Frood Sub-Series. The oldest Sudburian member in this area has been named the Frood sub-series; it consists of varying amounts of rhyolitic and andesitic volcanics with interbedded graywacke, arkose, and grit, which have been intruded by gabbro and Frood breccia. Its greatest recorded thickness (38) of 2,000 feet occurs south of Leach Lake, about two miles west of Copper Cliff and south and southeast of O'Donnell.

Copper Cliff Rhyolite. The next member of the Sudbury series, which Coleman and others called the Copper Cliff arkose, has been named the Copper Cliff rhyolite by the geologists of the International Nickel Company. It has been traced for a distance of nine miles westward from the town of Copper Cliff.

and some rocks that are found 14 miles to the southwest of Copper Cliff have the typical appearance of this much altered member which in places is coarse-grained and massive and in other places is tuffaceous and agglomeratic. Its maximum thickness, which Michener (38) estimated at 2,200 feet, occurs near its eastern end.

The relations between the Frood sub-series and the Copper Cliff rhyolite are believed to be conformable; but these are not clear, owing to the presence of Frood breccia which separates them.

McKim Graywacke. The top member of the Sudbury series is called the McKim graywacke; it is composed of graywacke with interbedded greenstone, pillow lavas, amphibolite, and rhyolite. In some places the graywacke is thinly bedded, often showing ripple marks and varve-like banding and in other places where the beds are thicker, cross-bedding is common. In the vicinity of Sudbury, Coleman estimated the thickness to be not less than 7,000 feet, but the measurement is difficult owing to the intrusion of gabbro and to the displacement by the Worthington fault.

It has been suggested that the upper surface of the Copper Cliff rhyolite, on which the McKim graywacke was deposited, may have been rather irregular, since the bedding of the latter is not everywhere parallel to the above surface.

Huronian - Bruce Series

Collins divided the Bruce series of Lower Huronian into the following five formations, from the youngest to the oldest:

Serpent quartzite
Espanola limestone
Bruce conglomerate
Mississagi quartzite
Ramsay Lake conglomerate

Fairbairn (26) agrees with Collins in the above classification of the Bruce series in the Sudbury area.

Ramsay Lake Conglomerate. Collins (19) considered the Ramsay Lake conglomerate to be a regolithic sediment and believed that it is separated from the McKim graywacke by an erosional unconformity and suggested that the conglomerate is composed of decomposition products of whatever rock formed the pre-Huronian surface. He stated that both conformity and unconformity of formations had been found, but that the conformable relations are apparent rather than real. Fairbairn (26) disagrees with this interpretation and cites four localities where he believes that conformable relations, between McKim and Ramsay Lake, are evident. Michener (38) also describes a section across the McKim-Ramsay Lake contact that appears to be a transition between them. In a number of places the contact between the top of the Sudbury series and the bottom of the Bruce series is confused by the presence of Frood type breccia which has sometimes been mistaken for a conglomerate. The

Ramsay Lake conglomerate is intermittently exposed parallel to the regional structure in a narrow zone that extends for many miles east and west of Sudbury. The maximum thickness has been estimated to be from 250 to 450 feet.

Mississagi Quartzite. The most widespread formation in the Sudbury area lies stratigraphically above the Ramsay Lake formation. It consists of coarse-grained, white to gray feldspathic quartzite layers from six to twelve inches thick, often cross-bedded and separated by thin layers of argillite, graywacke, or arkose. Coleman (12) placed this formation in the Sudbury series and called it Wanapitei quartzite; but Collins (20) shifted it to Lower Huronian and named it Mississagi quartzite. He estimated its maximum thickness to be approximately 8,000 feet in the Sudbury area.

Lawson (37) maintains that the stratigraphic sequence in this area has been misinterpreted and that the Sudbury series overlies the Mississagi formation and is therefore younger than the basal Huronian. His conclusions are based on very limited observations and, owing to his meager field experience in this district, he mistook a zone of Frood-type intrusive breccia for a basal conglomerate of the McKim graywacke. He believes that in some places this intrusive breccia is a great tillite (43).

Collins (17) was the first geologist to recognize the Bruce, Espanola, and Serpent formations in the Sudbury area.

Bruce Formation. The Bruce formation has often been mistaken for the Ramsay Lake, but Fairbairn (26) distinguished the Bruce, in Falconbridge and Dryden townships, from the Ramsay Lake by its different lithology and by its stratigraphic position above the Mississagi formation. He estimated that it has a maximum thickness of at least 2,000 feet.

Espanola Formation. The Espanola formation lies stratigraphically above the Bruce and consists mostly of thin-bedded graywacke and lesser amounts of dolomitic limestone; its total thickness is estimated at approximately 500 feet.

Serpent Formation. The Serpent formation is the top member of the lower Huronian in this area. Fairbairn (26) has identified it in Falconbridge township by its characteristic fine banding and its dead-white color. He estimated its total thickness at less than 3,000 feet.

Burrows and Rickaby (7, p. 13) grouped all the foregoing Keewatin and lower Huronian rocks as members of the Sudbury series and classified them as Timiskaming.

No rocks belonging to the middle Huronian have been identified in this immediate area.

Upper Huronian (Animikie) - Whitewater Series

The formations that lie within Sudbury Basin are isolated from the lower Huronian rocks by the Sudbury intrusive. Coleman (13) classified them as upper Huronian (Animikie), but stated that the correlation was uncertain, since it was largely lithological. Collins (16) suggested that, owing to their local nature, these formations be given the local name Whitewater series. Cooke (21), however, without stating his reasons, placed the Whitewater series in the Keweenawan; but nearly all other workers in this area agree with Coleman that the formations are probably Animikie in age. However, Yates (50) states:

> It is noteworthy, and may be highly significant that there are members of the Huronian series lying to the south and west of Sudbury that are unquestionably of volcanic origin, and resemble strikingly the rocks of the so-called Whitewater series. Outcrops are scarce at the eastern end of the Basin, particularly on the inner portion and relationships are obscured by the presence of complex breccias; so that details of the structure and timing are difficult to determine. All things considered it is probable that further structural and lithological studies will disclose that the Whitewater series is merely a part of the recognized and known Huronian, downfolded into a rather complex synclinorium and that the pre-existing structure controlled and determined the position and shape of the Sudbury Basin; the norite being intruded along the limbs and up the troughs of the syncline.

The writer has often noted the striking resemblance, as described by Yates, of some of the rocks that occur south of Sudbury basin to some of those of the Whitewater series; but much more structural and lithological evidence must be found before an acceptable solution can be offered regarding the age and stratigraphic position of the Whitewater series.

Some debatable points regarding the age relations of the rocks in this area have been needlessly confused by men who have expressed their opinions after short and hurried visits. Lawson (37) states:

> ... we have no recorded observations that justify the notion that this agglomerate (Whitewater) has suffered contact metamorphism. In a brief examination of the Whitewater series, extending from Fairbanks Lake across the Sudbury Basin to the Levack Mine, a section affording many excellent exposures, I found no evidence of contact metamorphism nor any dikes cutting the Whitewater rocks. Therefore, it appears to me, both from the failure of the record to establish contact metamorphism and from my own field observations, that the Whitewater series may possibly be a late pre-Cambrian resting on the eroded surface of the micropegmatite.

The writer considers the above statements by Lawson unwarranted. Coleman (11), Phemister (42), and Burrows and Rickaby (6) have recorded their observations of contact metamorphism, in the Whitewater series, adjacent to the Sudbury intrusive. Burrows and Rickaby also describe three types of dikes that intrude the Whitewater rocks; many of these are shown on the map No. 38g which accompanies their report; some of them are exposed along the roads and highways and should be recognized by any competent observer. The development of hornfelses and feldspathization in the Whitewater rocks adjacent to the Sudbury intrusive is so obvious that it is difficult to understand how this condition can be questioned by any observer.

<u>Onaping Volcanics</u>. Coleman (11) mapped the lower portions of the Whitewater series as Trout Lake conglomerate and

Onaping tuff. For many years this classification was accepted by the workers in the Sudbury area; but Burrows and Rickaby (6), after making a detailed study of these rocks during two field seasons, found no evidence of water-worn boulders or local sedimentary beds and concluded that Coleman's Trout Lake conglomerate is composed of volcanic breccias, agglomerate, lavas, and tuff. All workers who have followed Burrows and Rickaby, in this area, agree with them that these rocks appear to be a coarse phase of the Onaping volcanics.

There is a great variation in the distribution and size of the fragments found at the base of the Onaping volcanics, but the greatest number and largest sizes lie along the south range. These fragments consist of quartzite, granite, quartz, argillite, rhyolite, and andesite usually embedded in andesitic tuff. The most common type of fragment found along the south range consists of fine to medium-grained quartzite. Many of the fragments that lie in the northeastern part of Garson township are several hundred feet long; most of these occur in a breccia zone, several hundred feet wide, composed of smaller angular fragments of similar rock. Chute (9) mapped one of these fragments for an exposed length of 1,200 feet and a width that varies from 25 to 100 feet. Some fragments or residuals of similar rocks are frequently found within the micropegmatite for distances as great as 500 feet from the upper contact. Some phases of the lower Onaping volcanics that occur along the north range, strikingly resemble some of the intrusives that occur in the gneiss north of Sudbury Basin.

The coarse fragmental phase is followed by tuff that is characterized by an irregular diminution, in the size of the fragments, from the bottom to the top of the formation, where it is difficult, in the field, to distinguish it from the overlying slate.

The thickness of this formation has been estimated to be from 4,200 to 3,000 feet.

TABLE 4

CHEMICAL ANALYSES OF ONAPING VOLCANICS

	1	2	3	4	5
	per cent	per cent	per cent	per cent	per cent
SiO_2	59.02	61.43	69.66	60.44	74.00
TiO_2	0.45	0.49	0.42	0.68	0.43
Al_2O_3	10.84	10.11	12.86	16.10	11.35
Fe_2O_3	2.56	3.27	1.40	0.80	0.36
FeO	5.83	7.15	2.40	6.84	3.24
Fe (pyrrhotite)	1.32	----	----	----	----
FeS_2	----	----	----	----	0.21
CaO	4.09	3.09	1.16	trace	1.31
MgO	5.50	5.13	1.44	5.48	1.99
MnO	0.35	0.21	0.05	0.26	0.08
Na_2O	3.60	2.94	4.86	4.23	1.81
K_2O	2.72	2.87	3.36	3.97	3.74
P_2O_5	0.12	0.12	0.19	----	0.08
CO_2	0.36	0.05	0.13	0.07	0.05
C	0.58	0.48	----	----	----
S	0.96	0.91	trace	----	----
H_2O	2.00	2.02	1.73	1.40	1.60
	100.30	100.21	99.66	100.27	100.23

Nos. 1-2, by Coleman, Moore, and Walker (15), represent specimens taken near the type section near Onaping Falls; No. 3 represents a specimen of agglomerate or volcanic breccia from the northwestern part of the basin; No. 4, by Burrows and Rickaby (6, p. 17), represents a specimen of spherulite lava from the south central part of the basin; and No. 5, by the same authors, represents a specimen of rhyolite from the western part of the basin.

Onwatin Slate. Although the slate can be seen in only a few places, it is presumed to form a continuous bed between the Onaping volcanics and the Chelmsford sandstone. It has been proved, by diamond drilling, that it underlies much of the lake deposit that forms the surface between the outcrops of the volcanics and the sandstone. In places, the fine-grained tuff has good cleavage and, except for the absence of bedding, it is difficult, in the hand specimen, to distinguish it from the slate. This has led to the conclusion that these formations are conformable. An average thickness of the slate was estimated, by Coleman (11), to be 3,700 feet. Burrows and Rickaby (6) suggested that the slate is composed of the finer material of the Onaping volcanics.

Some thin-sections of slate consist of a few scattered, minute fragments of quartz, sericite, chlorite, and patches of carbonate in a dense, opaque, carbonaceous matrix. Other sections consist of thin bands, made up of a mixture of the above minerals alternating with thicker bands of the opaque material. See photomicrographs.

TABLE 5

CHEMICAL ANALYSES OF ONWATIN SLATE

	1	2
	per cent	per cent
SiO_2	58.62	66.57
TiO_2	0.70	0.24
Al_2O_3	15.30	7.65
Fe_2O_3	2.32	0.88
FeO	9.43	6.62
CaO	0.28	1.01
MgO	2.78	7.83
MnO	0.40	0.22
Na_2O	1.20	0.26
K_2O	3.50	0.70
CO_2	2.38	1.10
H_2O	2.90	3.83
P_2O_5	----	0.21
S	----	0.08
C	0.30	2.92
	100.11	100.09

Analysis No. 1 by Burrows and Rickaby (6), p. 28, and No. 2 by Coleman, Moore, and Walker (15), p. 39.

Chelmsford Sandstone. The Chelmsford sandstone is the youngest of the Whitewater series and outcrops in the center of the basin as a succession of parts of opposite limbs of folds whose axes are parallel to the long axis of the basin. These outcrops can be traced along a length of 20 miles, and across widths of from two to three miles. The dips of these limbs range from 20 to 50 degrees. The grain-size, which is mostly less than one millimeter in diameter at the gradational contact with the slate, increases towards the top, where some of the fragments approach five millimeters in diameter. Most thin-sections show that the rock is composed of a little less than 50 per cent quartz, the remainder being made up of varying amounts of feldspar, carbonate, mica, and opaque carbonaceous material. Burrows and Rickaby (6) state that they found occasional grains of micrographic intergrowth of quartz and feldspar, and suggest that the material was gathered from the surrounding micropegmatite and volcanic rocks. It may be possible that the material in the Onwatin slate and Chelmsford sandstone might have been derived from the Onaping volcanics; but it is improbable that any of this material came from the micropegmatite, since all the evidence proves that the micropegmatite is later than both these members.

Most of the thin-sections of sandstone consist principally of fine to medium-size grains of angular quartz and feldspar with considerable amount of mica and varying amounts of chlorite and carbonate. See photomicrographs.

Burrows and Rickaby (6, p. 30) give the following analysis of a sample of sandstone taken from the central part of the basin.

TABLE 6

CHEMICAL ANALYSIS OF CHELMSFORD SANDSTONE

	per cent
SiO_2	72.40
TiO_2	0.48
Al_2O_3	14.62
Fe_2O_3	0.24
FeO	3.67
CaO	0.72
MgO	1.99
Na_2O	1.82
K_2O	1.75
MnO	trace
H_2O	1.86
CO_2	0.40
C	0.27
	100.22

Fig. 2
Onaping tuff. Location 12,700 ft. S.E. from Sec. No. 67. X $20\frac{1}{2}$, plain pol. light.
Sec. NO. 105

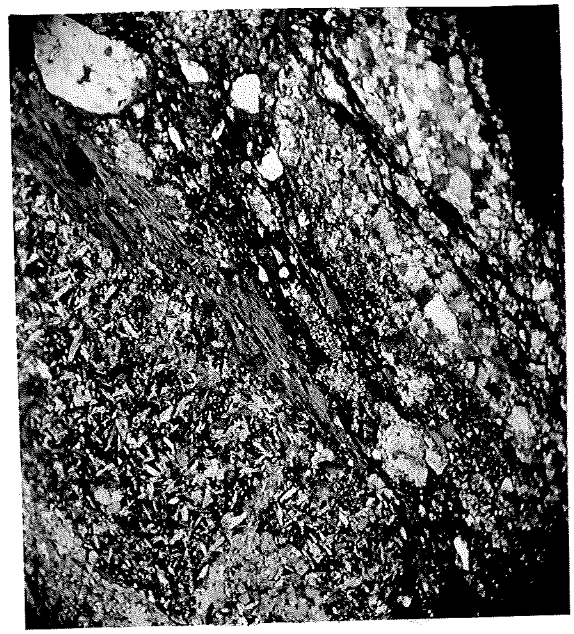


Fig. 3
Quartz, carbonates, and chloritic material in altered tuff. Loc. No. 2 shaft Errington mine. X $20\frac{1}{2}$, plain pol. light.
Sec. No. 50

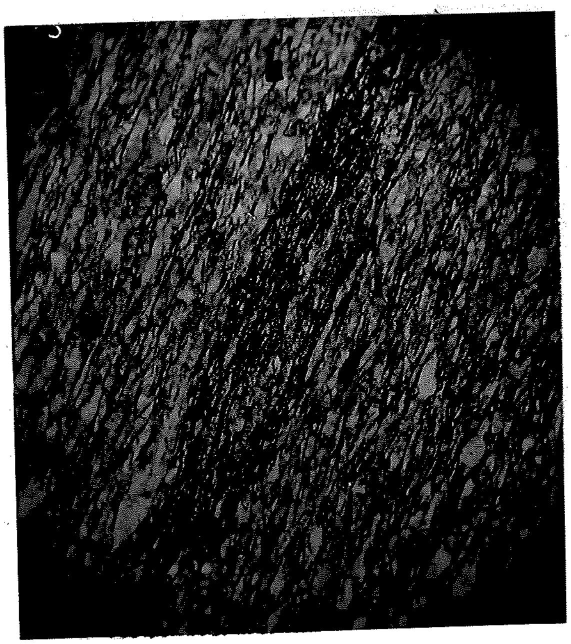


Fig. 4
Altered tuff with slaty cleavage. Loc. No. 1 shaft Errington mine. X $20\frac{1}{2}$, plain pol. light.
Sec. No. 45

Fig. 5
Hornfelsic tuff. Loc. lot 8, con. IV, Dowling twp. X $20\frac{1}{2}$, X-nicols.
Sec. No. 26

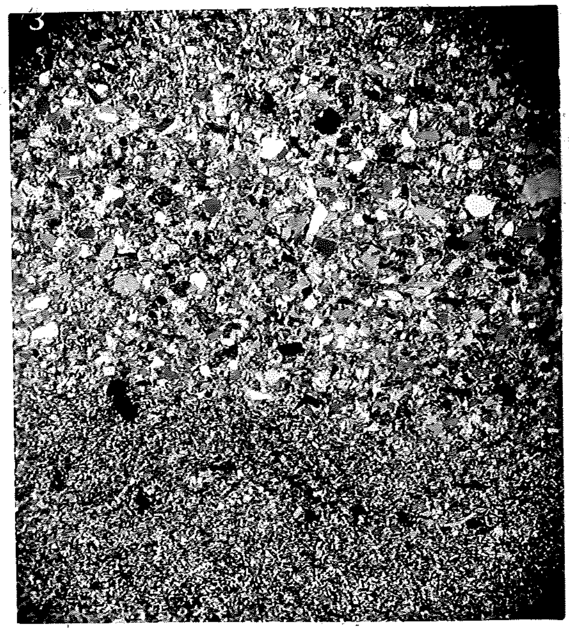


Fig. 6
Interbedded fine-grained sandstone and slate. Loc. lot 10, con. II, Balfour twp. X $20\frac{1}{2}$. X-nicols.
Sec. No. 13

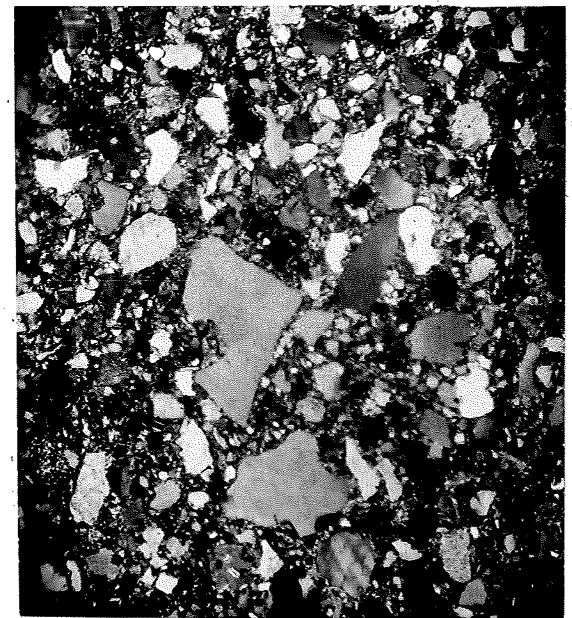


Fig. 7
Coarse sandstone. Loc. lot 12, con. IV, Balfour twp. X $20\frac{1}{2}$, X-nicols.
Sec. No. 28-B

Fig. 8
Graphitic slate with quartz and carbonate deposited along cleavage. Loc. Anthraxolite mine, lot 10, con. I, Balfour twp. X $20\frac{1}{2}$, plain pol. light.
Sec. No. 47

Fig. 9
Hornfelsic slate almost completely replaced by quartz and carbonate. Loc. No. 1 shaft, Errington mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 46

Granites

The Creighton granite, the largest of the granitic bodies in the south range, extends from Copper Cliff southwestward for a distance of about 13 miles, and varies in width from one to two and one-half miles. Although this mass has been mapped as a single unit, the rock shows variations in color, texture, and structure. The color ranges from dark gray to pink; the texture varies from porphyritic or crystalloblastic to equigranular; and the structure, although gneissic in most areas, is sometimes massive.

The age relation of the Creighton granite to the norite is controversial. Collins (18, Vol. 30) believed that this granite is older than the norite and explained the granite intrusions in the norite as the result of fusion of the granite contact by the later norite intrusive and the injection of the fused granite into the norite after the solidification of the border phase of the latter. Knight (35), Phemister (42), Yates (51), and many other workers in the field have cited evidence to prove that this granite is later than the norite, and Coleman (11) concluded that this is a composite body that includes both pre-norite and post-norite granites. Michener and his staff have studied this mass in considerable detail, and although he does not consider his evidence entirely conclusive, he states (38):

> Petrographically, it has been found that all the dike-like masses of granite in the norite have strongly recrystallized feldspar phenocrysts and strained and sutured quartz aggregates similar to those of the gneissic Creighton granite. Specimens of norite on the other hand, from Sta. M13, even though apparently surrounded by granite, are fresh and show no evidence of recrystallization or metamorphism.... In a few instances there is a slight granulation due to later movement along the contact, but this slight granulation does not approach the granulation and recrystallization of the granite. We have therefore the paradox of strongly metamorphosed textures in the granite dikes apparently intruding a norite which is fresh and unmetamorphosed in all cases.

But later in the report he describes another dike as follows:

> The most convincing granite dike in the norite occurs in lot 8, con. III, Snider twp., where a porphyritic granite dike 50 feet wide and at least 250 feet long strikes North 70 degrees West into the norite. It is composed of coarse massive porphyry and may be finer-grained at the norite contact. The one contact observable is sharp and appears to be slightly sheared on the norite side. The possible connection of the dike with the main granite body is drift-covered as is the farther end which disappears under an extensive drift area. The length is therefore not known. A thin section shows that the phenocrysts are not recrystallized to a fine-grained mesh but the micrographic quartz-feldspar intergrowth is very well developed.

The writer believes that much additional field and laboratory evidence is required before a definite conclusion can be offered regarding this problem.

The Murray granite is the second largest granitic body found adjacent to the southern edge of the norite. It has a length of a little more than three miles and a maximum width of a little more than one mile. It is fine to medium-grained and is composed chiefly of quartz, microperthite, biotite, microcline, and orthoclase. A number of apophyses of this body extend for various distances into the norite, and irregular masses of similar granite, up to 400 feet wide, are found intruded into the norite more than a mile west of the Murray granite-norite contact. The following chemical analyses given by Coleman (15) show the similarity of these irregular intrusive masses to the granite at the contact of the norite.

TABLE 7

CHEMICAL ANALYSES OF MURRAY GRANITE

	79	80
SiO_2	76.40	74.40
TiO_2	.34	.25
Al_2O_3	11.10	10.69
Fe_2O_3	.94	.94
FeO	.88	1.54
CaO	1.48	.72
MgO	.76	.75
MnO	.01	.01
Na_2O	2.84	2.78
K_2O	5.72	6.52
H_2O	.55	.89
CO	.37	.04
P_2O	.05	.01
S	.01	.03
	99.65	99.60

79 - Granite, 2 miles northwest of Murray mine (in norite).
80 - Granite, Murray mine contact with norite.

TABLE 8

SPECTROGRAPHIC ANALYSES OF GRANITES

		Si	Ag	Al	Ca	Co	Ni	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Sr	Ti	V	Zr
Murray Granite																			
Number	Location																		
8273-13	1' from norite	4½	—	10	10	—	tr	½	4	2	6½	6	4½	1½	8	4	4	tr	tr
8273-14	6' from norite	5	—	10	9	—	tr	1	4½	2	6	6	5	1½	8	2	4	tr	tr
8138-C	500' from norite	4	—	6	7	—	tr	½	3½	1	6	5	3	½	8	½	2	tr	—
8138-D	1000' from norite	2½	—	4	7	—	—	tr	1	½	6	2	2	½	8	1	1	—	—
Granite Plug Intruding Norite approximately 1 mile N.W. from Murray mine																			
Number																			
8216-11		5	tr	6	8	—	4	½	6	½	6	2	2	½	8	1	1	—	—
8216-13		3½	—	10	9	—	tr	tr	3½	½	6	5	2	tr	7	1	2	—	—
8216-15		3	—	5	8	—	tr	tr	5	½	5	3	2	tr	7	1	2	—	—
8216-17		5	—	9	9	—	tr	½	5	½	½	5	3	1	7	2	2	—	—
Creighton Granite																			
Number																			
7612-C		2	—	6	9	—	—	1	1	½	6	4	3	½	6	1	1	tr	—
7610		2	—	6	8	—	—	½	½	½	6	4	2	tr	6	½	1	tr	—
7614-C		2	—	5	8	—	—	½	½	½	5	4	2	tr	6	½	1	tr	—

Elements not present include As, Ba, Be, Bi, Cd, Co, Pb, Sb, Sn, Zn.

The intensities of the spectral lines were estimated on a 0-10 basis. The samples were arced under similar conditions and all exposures were made on the same plate. The results therefore should be roughly comparable. There was no good check on amount of exposure, as no element was constant enough to act as an internal standard.

Analyses by Dr. H. D. B. Wilson, in the Copper Cliff laboratory of the International Nickel Company of Canada, Limited.

The similarity of these granite masses was confirmed by the spectographic analyses of the minor elements, shown in Table 8. Sample No. 8216-17 was taken from the edge of the plug and contained inclusions of norite material; this accounts for the relatively low K in this sample.

Quartz Diorite

A number of dikes that intrude the footwall rocks and some irregular masses that occur at various places along the base of the norite have an average chemical composition of the norite, but they have a finer-grained texture with more micrographic intergrowth and an average mineral composition of quartz diorite. Coleman believed that these dikes are apophyses from the norite and called them "offsets," and many later workers have agreed with Coleman's observation. The Foy offset has often been described as continuous with the norite, however, an excellent surface contact of this offset with the norite was shown to the writer by Dr. A. B. Yates, and several diamond drill cores were shown to the writer, by Dr. W. S. Savage, in which the contact between the norite and the Foy offset rock is definite and sharp, although no chilling could be recognized in either rock.

Yates (51, pp. 163-169) shows that no evidence has been found to prove that direct connections exist between the Copper Cliff, Foy, Worthington, or Frood offsets and the main norite mass. However, a norite dike that penetrates the foot-wall rocks adjacent to the Creighton bay appears to have a transitional contact with the rock within the bay.

The rock in the marginal masses differs, somewhat, from that in the offset dikes in that it is usually less altered and contains more orthorhombic pyroxene and less quartz, and the texture is more often hypautomorphic granular.

These dikes and masses differ from the usual intrusive type in that they are composed of varying amounts of angular to sub-angular fragments of older rocks embedded in a matrix that, in the dikes, is usually composed of andesine, secondary amphiboles, micrographic intergrowth of quartz and feldspar, and minor amounts of quartz, biotite, apatite, magnetite, and leucoxene. The matrix of the marginal masses usually is composed of andesine, orthorhombic and clino-pyroxenes, amphibole, quartz, biotite, apatite, and magnetite. The fragments constitute from 0 to 75 per cent of the rock and range from microscopic sizes to masses more than 100 feet long; many of these fragments differ from the wall rocks and must have been transported from considerable distances.

The microtexture of the matrix of these rocks ranges from hornfelsic in some sections to fine-grained hypautomorphic-granular in others; in many sections some of the matrix has been recrystallized to a micrographic intergrowth of quartz and feldspar.

Yates (51, p. 160) in the following table compares the averages for many analyses of offset rock, presented by W. H. Collins, with the average for twenty-five analyses of norite:

TABLE 9

ANALYSES OF OFFSET ROCKS AND AVERAGE NORITE

	Worth-ington	C. Cliff	Frood	Foy	Frood North (new)	Average Norite
SiO_2	57.72	58.18	59.76	58.59	54.25	55.32
Al_2O_3	16.60	15.25	15.65	16.21	15.26	17.62
Fe_2O_3	2.29	2.26	1.90	2.19	-----	1.82
FeO	7.45	6.62	5.96	5.79	11.63	5.49
CaO	5.81	7.40	5.90	5.48	6.88	7.18
MgO	3.60	4.37	4.05	4.27	4.54	5.51
Na_2O	2.28	2.47	2.90	2.88	5.38	2.35
K_2O	2.08	1.89	1.88	2.41	0.67	1.64
H_2O	1.20	1.14	1.04	0.86	1.04	1.34
TiO_2	0.77	0.86	0.84	0.84	0.75	0.72
P_2O_5	0.31	0.27	0.21	0.27	-----	0.16
S	0.28	0.20	0.19	0.24	0.10	----
CO_2	0.17	0.01	-----	0.03	0.18	0.12
Sp. Gr.	2.877	2.892	2.940	2.857	2.88	2.817

Eight representative specimens of quartz diorite from the various offsets and six typical specimens of the norite from various parts of the intrusive were selected for analysis (38).

The pulps were sampled carefully and all arced on the same plate. As the silica in the samples has a very small variation it could be used as an internal standard to determine whether the exposures were the same for all samples. The silica lines were found to be approximately equal in all the samples so the weights of any line of an element were comparable and indicated approximate concentrations of the element in the sample.

Table 10 presents Michener's spectrographic analyses, followed by the statement:

The spectrographic analyses of the minor elements of the norite and quartz diorite confirm the evidence of the chemical analyses of the major elements in showing that the chemical composition of the two rocks are very similar. The only spectrographic difference that showed up at all was in the titanium content, and even in this case an overlapping was found. A study of the numerous chemical analyses of the rocks also shows that there is no consistent difference in the amount of titanium in the two rocks.

Yates (51, pp. 159-160) states:

The rock from place to place varies considerably, mainly due to alteration and to mineralization so that it is difficult to determine an average composition. The following table indicates the range of percentages of the component minerals see Table 11 .

Collins (18, Vol. 28, pp. 162-163) states:

The offset rock in all these offsets is so much alike that specimens from any two bodies cannot be distinguished by chemical or petrographical means. ... Its composition is indicated by the following table of Rosiwal analyses.

TABLE 10

COMPARATIVE SPECTROGRAPHIC ANALYSES OF QUARTZ DIORITE AND NORITE

	Ag	Al	B	Ba	Co	Cr	Cu	K	Mg	Mn	Mo	Na	Ni	Pb	Sn	Sr	Ti	V	Kn	Si
Quartz Diorite Number																				
7570-3	ftr	7	¼	1½	2	¼	--	6	1	6	1	8	1	1	--	½	6	5	tr	7
7549	tr	8	¼	1½	2	tr	¼	6	1	6	1	8	2	½	--	1	6	5	tr	7
7540	½	7	½	1	3	¼	1	7	1	6	2	8	6	½	--	¼	5	5	tr	6
7493-A	ftr	9	¼	2	2	¼	¼	7	1	6	2½	8	3	1	--	2	6	5	tr	7
7367	ftr	7	¾	½	2	-	ftr	7	1	6	2½	8	1	2	--	½	6	6	tr	6½
7350	tr	9	¼	3	1	¼	ftr	7	1	6	2½	8	2	1	--	2	6	5	--	6
4799	ftr	8	tr	1	2	tr	ftr	7	½	6	1	9	1	2	--	½	7	5	tr	7
4797	ftr	7	¼	1	2	¼	tr	7	1½	6	1½	9	3	2	--	tr	7	5	tr	7
Norite Number																				
2411	--	7	¾	1	2	½	--	6	3	6	2	8	1	1	--	1	2	4	--	6½
2412	ftr	6	¼	½	2	½	ftr	6	2	6	2	8	3	1	--	½	2	4	--	6½
3309	--	9	¼	2	2	¼	ftr	7	1	6	1	8	2	½	--	2	3	4	ftr	7
2407	ftr	7	tr	½	2	¼	ftr	6	1½	6	1½	8	2	1	--	¼	2	5	ftr	7
4381	--	9	tr	1	2	¼	--	6	1½	6	2	8	1	½	--	3	3	4	ftr	7
4377	ftr	9	½	2	1	¼	tr	7	2	6	½	8	1	1	--	3	5	5	ftr	7

Ca and Fe very strong in all samples

Elements sought and not present include Bi, Cd, Ce, Cs, Ge, Li, In, Ir, Sc, and La.

TABLE 11

RANGE OF PERCENTAGES OF THE COMPONENT MINERALS IN OFFSET ROCK

	Yates per cent	Collins per cent
Andesine feldspar	55 - 80	-- --
Plagioclase	-- --	34.8 - 43.9
Hypersthene and diallage	10 - 30	-- --
Amphibole	5 - 15	-- --
Hornblende	- - --	27.7 - 37.9
Quartz	3 - 20	10.9 - 12.0
Biotite	1 - 10	5.4 - 14.0
Apatite and ilmenite	1 - 3	-- --
Titaniferous magnetite	- -	1.0 - 4.7
Apatite	- -	0.05 - 1.0
Sulphide	- -	0.5 - 0.7
Micrographic intergrowth	- -	0.5 - 6.3
Titanite	- -	0.1 - 0.2

The mineral composition of some of the samples of the offset rock taken by the writer correspond to Yates' analysis and others correspond to Collins' analysis.

Collins (18, Vol. 30, p. 52) states that samples of rock from the Worthington offset and norite from the Creighton mine were submitted in 1934 to Professor A. C. Lane, chairman of a committee of the United States Research Council for the Measurement of Geologic Time by Radioactive Methods (according to their contents of radioactive elements and helium, the gaseous end product of radioactive decay). The following results were reported:

Quartz diorite, Worthington dike	530 plus or minus 15 million years
Norite, Creighton mine	550 plus or minus 15 million years

Age indicators: Ra, Th, He.

Frood Type Breccias

The breccia at Sudbury has been described by Yates (51, pp. 169-171) and Fairbairn and Robson (27). This unusual type of rock occurs over a wide area in the Sudbury district. It is composed of all shapes and sizes of fragments of various rocks embedded in a fine-grained matrix. Although some of the fragments are of rocks that must have been conveyed over long distances, most of the fragments are from the adjacent wall rocks. The composition of the matrix varies with the character of the included fragments. The variability of the matrix is shown in the mineralogical analysis given by Yates (51, p. 170), presented on the following page in Table 12. The composition of one section is given as 60 per cent quartz and 40 per cent augite. These minerals have none of the characteristics of those found in orthomagmatic rocks; they show no order of crystallation.

TABLE 12

RANGE OF PERCENTAGES OF COMPONENT MINERAL IN MATRIX

	per cent
Hornblende	3 - 50
Biotite	5 - 20
Quartz	5 - 20
Oligoclase	5 - 20
Orthoclase Microcline Albite	0 - 10
Sphene	0 - 2
Metallics	1 - 3
Chlorite Clinozoisite Calcite Epidote	0 - 3

Fairbairn and Robson (27, pp. 20-21) divided these breccias into three types: (1) vein and stockwork breccias occur entirely within a single formation; (2) contact breccias occur at the boundary of two formations; (3) injection breccias have similar characteristics to those of (1) and (2) but are composed of fragments and matrix that are foreign to the host rock.

With the one exception, that of the Creighton granite-norite contact, (2) type of breccia is found, in some places, along every major contact in the area.

Chilling adjacent to the walls of the Frood type breccia has never been observed. As reported by Fairbairn and Robson (27), hydroxyl (OH-bearing) minerals - chlorite, sericite, epidote-clinozoisite, etc. - are usually more abundant in the matrix than in the fragments, and the margins of some of the fragments are richer in the hydroxyl minerals than the centers. They also reported a marked gain in soda in the matrix of all types that were studied.

The process of brecciation is believed to have begun by crushing and partial rotation of fragments, followed by the introduction of corrosive fluids and gases. The continued attrition of the fragments produced a matrix which ranges from 35 to 85 per cent of the total volume. In this condition the matrix possessed some of the properties of an igneous magma and transported the included fragments for distances up to thousands of feet.

FIG. 10

FROOD BRECCIA IN CUT ALONG SUDBURY-CAPREOL ROAD
Lot 4, Conc. VI, McKim Twp.

Trap Dikes

Two ages of trap dikes, which are separated in time by the Frood breccia and the ore-bearing quartz diorite, occur in the south-central and southwestern part of the area. The older traps have been recognized in only a few places, where they are chilled against Creighton granite and cut by Frood breccia. They have an intergranular texture, with hornblende constituting 55 to 70 per cent of the rock, the remainder being feldspar and quartz. The younger traps resemble the older traps in appearance, and form a prominent east-west system between Crean Hill and Copper Cliff. They are composed of 55 to 70 per cent andesine feldspar, 30 to 40 per cent hornblende, and minor amounts of quartz and magnetite. One of these cuts and is chilled against mineralized quartz diorite of the Copper Cliff offset, and several have been observed that cut and are chilled against Frood type breccia.

Olivine Diabase Dikes

The youngest and most prominent system of late intrusives in the area is made up of a series of olivine diabase dikes that vary from a foot to more than 300 feet in width. These dikes occur in segments, up to 10 miles in length, that are often offset to the left and frequently overlap each other. They appear to have filled tension fissures that were produced by torsional stress. Their strike varies from N. 20 degrees W. to N. 40 degrees W., and their dip is nearly vertical. Their texture is intergranular, except at the chilled edges, and varies from fine to coarse-grained to porphyritic. The color on fresh surfaces is gray, but weathered surfaces are brown. The principal minerals are labradorite, augite, olivine, magnetite, and ilmenite.

III

THE SUDBURY INTRUSIVE

Field Relations - Shape and Size

The outcrop of the Sudbury intrusive has the form of an irregular ellipse having a major axis approximately 37 miles long and a minor axis of approximately 17 miles. Direct observations regarding the shape of the intrusive have only been made in the mines and by diamond drilling. This work has indicated that the outer edge of the Sudbury intrusive on the north range has an average dip of approximately 40 degrees toward the center. The very limited amount of work on the east range indicates the dip to be nearly vertical in that area. Observations made in the mines situated in areas along the south range indicate the dip to be between 40 and 60 degrees toward the center; the dip of the outer contact of the intrusive has been obscured by faulting at Garson, Falconbridge, Kirkwood, and Crean Hill mines. There are no operating mines on the west range, but diamond drilling along the contact in this area has indicated a dip of approximately 30 degrees toward the center (44).

Dips Observed Along the Outer Edge of the Norite

South Range

Crean Hill (fault contact)	from 60° S. to vertical
Creighton (intrusive contact)	average of about 45° toward center
North Star (intrusive contact)	75°-80° toward center
Gertrude (intrusive contact)	55°-67° toward center
Murray (intrusive contact)	35°-40° toward center
Kirkwood (fault contact)	vertical
Garson (fault contact)	80° S.
Falconbridge (fault contact)	85° S. to vertical

East Range

Very little information, but indications are that the dips are vertical.

West Range

Limited information indicates dip of 30°-45° toward center.

North Range

Levack and adjacent area (intrusive and brecciated contacts) 40°-45° S.

Description of Contacts

The lower contact of the norite, as seen in the surface exposures along the North and East ranges, is a fine-grained phase. It is highly feldspathic with visible grains of quartz, most of which are milky white, although an occasional sapphire-blue grain can be seen.

In the underground workings in the Levack mine and in diamond drill cores from that vicinity, an unusual condition is sometimes seen at the lower contact of the normal norite. At some of these places the normal norite is underlain by an irregular zone, 25 to 50 feet in width, consisting largely of recrystallized plagioclase; below this is a zone of basic norite, and below the latter is a zone of peridotite breccia.

The norite along the South range contact varies from fine-grained to coarse-grained phases. These contact phases usually have an abundance of sapphire-blue quartz grains and considerable amounts of biotite. In some places, along the South range contact, the norite shows the effect of shearing and the development of chlorite and biotite in alignment produces an incipient schistosity.

Only a small fraction of the actual contact of the micropegmatite with the Onaping volcanics is exposed; in most of these places the contact appears transitional over widths varying from a few to many feet.

Theories as to Emplacement and Differentiation

Many geologists accept Coleman's conception (15) of the Sudbury intrusive as a basin-shaped laccolith. (Later Grout (29) called this form of intrusive "lopolith.") Moore and Walker (15) supported Coleman in developing the theory that the norite-micropegmatite is the result of magmatic segregation in a homogenous magma that was intruded, as a sheet a mile and a quarter thick, along a plane of weakness beneath the Whitewater series. They interpreted the shape of the basin to be due to an ebb in the magma chamber, while the magma was liquid, thus causing a collapse of the underlying floor of older rocks.

Knight (36) was the first worker to question Coleman's concept of a basin with gentle slopes toward the center. He stated that the dip, in many places along the south edge of the intrusive, is nearly vertical and in some places the dip is away from the basin. He suggested that the present shape of the intrusive may be the result of down-faulting of the basin in one great fault block and that the intrusive may be in the form of a huge ring-dike that surrounds the fault block.

Collins (18) stated his reasons for believing that the Sudbury intrusive was intruded as a thick sheet or sill, almost exactly horizontal, between the Whitewater series and the maturely eroded floor of older rocks on which the Whitewater series was deposited. He believed that the norite, transition zone, and micropegmatite are the result of magmatic segregation, and that this composite sill solidified in this position, the present shape being caused by later organic forces.

Bain (1) attempted to show that the Sudbury intrusive has assimilated an amount of rock equivalent to two-thirds of its original volume, and possibly two to three times that amount. He concluded that the intrusive shows a variation curve, from the base upwards, which can not be explained on the basis of simple magmatic differentiation, regardless of whether differentiation occurred by gravitational settling of crystals or by liquid immiscibility.

Phemister (42) made mineralogical analyses of samples which he had collected, at regular intervals, along eleven traverses across the Sudbury intrusive, and concluded that a theory of gravitative differentiation in situ can not account for the different phases of the Sudbury intrusive. He regarded the norite and micropegmatite as two separate intrusions.

Petrographic Description of the Sudbury Norite Megascopic and Microscopic

The geological staff of International Nickel Company has been engaged for many years in studying and mapping in detail the Sudbury intrusive and the adjacent footwall rocks.

A part of this work consisted of running fifty traverses across the South range, at intervals of about one-half mile. More than 600 specimens of the Sudbury intrusive were collected to represent all the apparent changes in the rocks. Specific gravity determinations were made on all the specimens, and thin sections of many of them were studied.

The writer was given permission to study all the information compiled in connection with the above work. In addition to several hundred specimens collected by the writer along similar traverses across various parts of the intrusive, he was given more than 100 specimens collected along seven of the above-mentioned fifty traverses made by the geological staff of the International Nickel Company. These geologists classified the norite according to color, texture, and specific gravity into the following four types:

1. Normal norite is characteristic of most of the South range and constitutes more than one-half of the norite in this area.

2. Gray norite takes the place of the normal norite at the eastern and western ends of the South range.

3. Marginal norite is a micaceous, somewhat more siliceous phase which occurs along the footwall of the central one-third of the South range norite.

4. Pegmatitic norite is a coarse-grained, variable phase which often occurs between normal norite and transition rock.

Description of the Four Types

Normal norite is a medium-grained rock varying in color from dark greenish gray to almost black. The black norite is confined longitudinally to the central part of the South range; this merges with a gray-green type which occurs along the eastern and western parts of this range. Both types are characterized by the dark color of the lath-shaped plagioclase which, in most cases, is so dark that in the hand specimen it might be mistaken for amphibole.

The rare fresh specimens of normal norite have an intergranular texture and are composed of 60-80 per cent feldspar (55-65 per cent An), 15-30 per cent pyroxenes (hypersthene, pigeonite, diopside, and augite), 5-10 per cent quartz. 0.25-5 per cent magnetite, and minor amounts of apatite, rutile, and zircon.

In most of the thin-sections the pyroxenes are altered to a fibrous mixture of tremolite and actinolite, and biotite. These secondary products are often confined within the original crystal outlines.

The feldspar occurs in large laths, usually colored brown with minute inclusions of magnetite or ilmentite. The feldspar is earlier than the augite but later than the other pyroxenes. Coarse-grained quartz sometimes fills the interstices between the feldspar and the augite crystals, with some corrosion of the earlier minerals. Magnetite is closely associated with augite and is commonly surrounded by a rim of leucoxene. Apatite and zircon are minor accessories, occurring in the feldspar.

The gray-green phase is slightly more feldspathic than the black, and, in general, is more altered. The tremolite and actinolite tend to spread from the original crystal boundaries of the pyroxenes, and replace the feldspar along cleavages and fractures. The feldspar is mostly gray colored and the cores are partly altered to epidote, zoisite, and amphibole. Rosiwal analysis of a typical thin-section showed approximately 70 per cent plagioclase, 15 per cent amphibole, 12 per cent quartz (includes that contained in minor amounts of micrographic intergrowth), 2 per cent biotite, and minor amounts of apatite, epidote, magnetite, and zoisite.

Western gray norite is a medium to coarse-grained rock with a hypautomorphic-granular texture. The feldspar tends to be equidimensional in form, and is light gray, white, or pink in color, and is more or less saussuritized. The pyroxenes have been altered to hornblende, actinolite, tremolite, and biotite. Gray norite contains more quartz than the dark, normal type; Rosiwal analysis of a typical thin-section showed approximately 60 per cent feldspar (almost completely saussuritized), 20 per cent quartz (including that contained in the micrographic intergrowth), 19 per cent amphibole and biotite, 1 per cent magnetite, and a small amount of apatite.

Marginal norite is light-colored and resembles the western gray norite, except that it contains considerable more biotite. It differs from normal norite in that the feldspar is slightly more calcic and is free from brown inclusions. Most of the quartz is coarse and corrodes the feldspar laths, but some occurs as a micrographic intergrowth with the feldspar. Rosiwal analysis of a typical thin-section showed 55 per cent labradorite, 20 per cent quartz (including that which occurs as micrographic intergrowth with the feldspar), 20 per cent amphibole, 4 per cent biotite, and a small amount of magnetite and apatite.

The pegmatitic norite is characterized by variable grain-size and variable, but high, original pyroxene content now completely uralitized, with these alteration products having partly replaced the intervening feldspar which is almost completely saussuritized. Rosiwal analysis of a typical section showed approximately 50 per cent feldspar, 35 per cent amphibole, 10 per cent quartz, 4 per cent biotite, and minor amounts of apatite and magnetite. Remnants of the original feldspar were found to be less calcic than the feldspar in the normal norite.

The description given for the western norite also applies to the norite of the northern range.

Transition Zone

The width of the transition zone varies from 200 to several hundred feet. In some sections this zone consists of a confused mixture of granitized rocks intruded by aplitic dikes. In other sections there is a gradual increase of feldspar and a decrease in mafic minerals across the zone until the rock becomes a typical micropegmatite. In some sections, along the South range, the rock in this zone has the appearance of an amphibolite; thin-sections of this type always show a large proportion of epidote.

Yates (61) compares the range and average analyses of 25 specimens of norite, selected from all available sources, with the average analysis of the norite specimens collected by Collins (18) along his Levack, Capreol, Maclennan, and Creighton traverses. (See Table 13.)

Micropegmatite

Megascopic Description

More than one-half of the exposed surface of the Sudbury intrusive is micropegmatite. The color varies from pinkish red to dark or greenish gray, and resembles a medium-grained granite in some places and granodiorite in others.

TABLE 13

CHEMICAL ANALYSES OF NORITES (61)

	Average	Range	Collins' Average
SiO_2	55.32	51.52 - 59.65	55.16
Al_2O_3	17.62	14.50 - 21.64	16.86
TiO_2	0.72	0.36 - 1.39	0.83
P_2O_5	0.16	0.03 - 0.41	0.25
Fe_2O_3	1.82	0.47 - 4.90	1.94
FeO	5.49	5.28 - 7.02	6.50
CaO	7.18	5.41 - 8.62	7.42
MgO	5.51	3.88 - 7.98	5.17
K_2O	1.54	0.70 - 2.50	1.35
Na_2O	2.35	2.25 - 3.87	2.87
H_2O	1.34	0.58 - 1.80	1.28
MnO	Trace	- -	0.10
CO_2	0.12	0.05 - 0.31	0.15

"Careful calculations made by Dr. H. J. Fraser on specimens close to the above averages show the following mineral composition, where the rock is reasonably fresh":

TABLE 14

CALCULATED MINERAL COMPOSITION OF NORITES

	Per Cent
Labradorite	55
Potash feldspar	3
Hypersthene	14
Diallage	9
Quartz	12
Biotite	1
Amphibole	3
Titanite) Ilmenite) Magnetite)	2
Apatite	3/4

Most of the feldspars have a dull appearance, and the mafic minerals appear to be altered and have ragged outlines.

Microscopic Description

The micropegmatite of the Sudbury intrusive is composed of variable amounts of micrographic intergrowths of quartz and feldspar, granular quartz, chlorite, epidote, hornblende with rare residuals of pyroxene, leucoxene, zoisite, calcite, and minor amounts of other accessory and secondary minerals. The amount of quartz-feldspar intergrowth varies from zero to 75 per cent of the rock. The intergrowths show a great variety of detail, and dimensions of the components are not uniform. Most of the frets are composed of intergrowths that are finest at the center and coarsest at the margins, but occasionally a fret is seen where the coarsest texture occurs between finer intergrowths at the center and the outer margins. In some frets the boundaries between the quartz and the feldspar appear to be fairly sharp, but in many cases they are ragged and hazy, and many patterns do not resemble cuniform characters.

The Writer's Interpretation Regarding the Formation of the Micrographic Intergrowths in the Sudbury Micropegmatite

For the past fifty years most geologists have accepted T. L. Walker's (48) theory that gravitative differentiation, in the molten magma, had resulted in the formation of norite at the base and micropegmatite at the top of the Sudbury intrusive. It followed, quite naturally, that the consensus of geologic opinion has been, and still is, that the micrographic intergrowths of quartz and feldspar in this rock are the result of crystallization from the original magma. The writer does not agree with the above opinion and submits the following suite of photomicrographs to support his belief that these intergrowths are the result of replacement of feldspar by quartz. These photomicrographs were made from thin-sections of specimens that were collected along the Canadian Pacific Railway from the base of the norite near Windy Lake to the top of the micropegmatite southeast of Levack Station. These photomicrographs show that the intergrowths of quartz and feldspar are not confined to the micropegmatite, but also occur in variable amounts throughout the norite and in the Onaping tuff. Some specimens collected by the writer from widely separated places in the micropegmatite, show no micrographic intergrowths of quartz and feldspar; the rock represented by these specimens is a medium-grained granite.

The writer has found that the composition of these intergrowths in a single section is variable. Some intergrowths consist of quartz and albite; there are some in which the feldspar near the center of the fret is albite and that near the outer margin is orthoclase containing ragged patches of albite, and some rare cases in which the feldspar is anorthoclase.

Sometimes the intergrowth radiates from a partly or almost wholly replaced feldspar crystal, but often not even a remnant of the older crystal remains at the center. In some crystals the replacement began at the edges and ends or along twinning and cleavage planes, and in others at the center. Most of the feldspar which has not been replaced by the quartz-feldspar intergrowth has been altered to sericite, epidote, chlorite, carbonate, and kaolinitic material, and most of the early mafic minerals have been altered to secondary amphibole, chlorite, magnetite, and leucoxene; but remnants of pyroxene, hornblende, and biotite are seen in some sections.

After examining hundreds of thin-sections of specimens of micropegmatite, collected from widely separated places within Sudbury basin, the writer has been unable to find any petrographic evidence that indicates that the micrographic intergrowth of quartz and feldspar, in this rock, is the result of primary crystallization from a silicate melt. On the other hand, the evidence as shown and explained in the following photomicrographs, appears to him to be most cogent in favor of the formation of these micrographic intergrowths by replacement.

Yates (51) compiled the following table from thirty selected analyses of the Sudbury micropegmatite.

TABLE 15

CALCULATED AVERAGES OF 30 SELECTED CHEMICAL ANALYSES OF SUDBURY MICROPEGMATITE

	Average of 30 Analyses	Range
SiO_2	67.83	63.29 - 72.60
Al_2O_3	13.36	11.46 - 16.08
TiO_2	0.68	0.19 - 1.29
P_2O_5	0.21	0.10 - 0.35
Fe_2O_3	1.28	0.54 - 5.55
FeO	4.39	2.88 - 5.71
CaO	2.04	1.08 - 5.38
MgO	1.50	0.67 - 2.19
K_2O	3.82	1.25 - 5.48
Na_2O	3.39	1.98 - 5.17
H_2O	1.21	0.51 - 1.96
CO_2	0.17	0.01 - 0.67
	99.88	

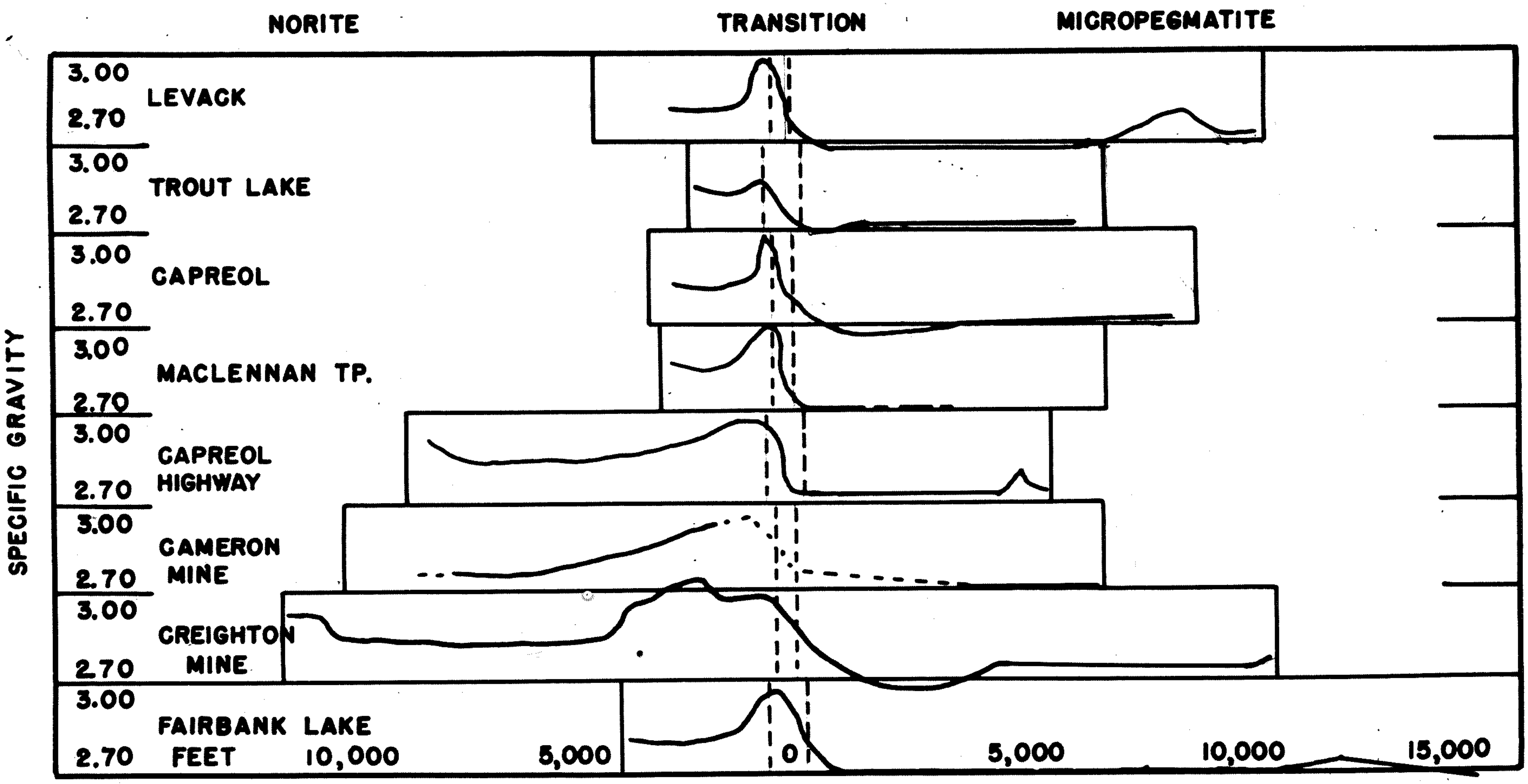


FIG. 12— CURVES OF SPECIFIC GRAVITY VARIATION ACROSS THE SUDBURY INTRUSIVE.

(AFTER COLLINS)

PHOTOMICROGRAPHS OF THIN-SECTIONS OF SPECIMENS COLLECTED ALONG A TRAVERSE ACROSS THE SUDBURY INTRUSIVE FROM THE BASE OF THE NORITE NEAR WINDY LAKE TO THE BASE OF THE ONAPING VOLCANICS SOUTHEAST OF LEVACK STATION ON THE MAIN LINE OF THE CANADIAN PACIFIC RAILWAY

Fig. 13
Labradorite partly replaced by quartz. Loc. base of norite near Windy Lake. X $20\frac{1}{2}$, X-nicols.
Sec. No. 67

Fig. 14
Labradorite partly replaced by quartz. Loc. 655 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 70

Fig. 15
Labradorite partly replaced by quartz. Loc. 710 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 72

Fig. 16
Almost completely saussuritized feldspar partly replaced by quartz. Loc. 1365 ft. S.E. from Sec. 67.
Sec. No. 75

Fig. 17

Andesine partly replaced by quartz. Loc. 1450 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols. Note: these feldspar are much less altered than those in Sec. 75.

Sec. No. 76

Fig. 18

Andesine partly replaced by quartz. Loc. 1485 ft. S.E. from Sec. No. 67. X $20\frac{1}{2}$, X-nicols. Note slivered end of feldspar crystal near center.

Sec. No. 77

Fig. 19

Andesine partly replaced by quartz. Loc. 1545 ft. S.E. from Sec. 67. X 45, x-nicols. Note: zoisite crystal partly replaced by quartz.

Sec. No. 78

Fig. 20

Saussuritized feldspar partly replaced by quartz. Loc. 1895 ft. S.E. from Sec. 67. X 45, X-nicols.

Sec. No. 79

Fig. 21
Almost completely saussuritized and kaolinized feldspar partly replaced by quartz. Loc. 1495 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, plain pol. light.
Sec. No. 80

Fig. 22
Almost completely saussuritized feldspar partly replaced by quartz. Hazy twinning visible in residual feldspar. Loc. 1995 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 81

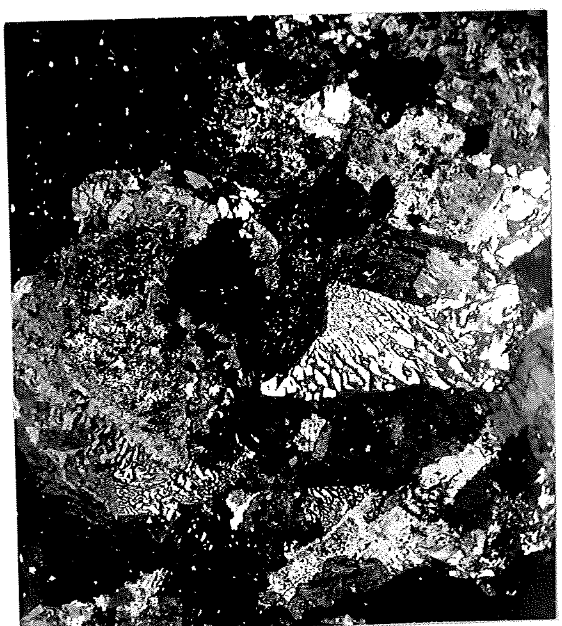


Fig. 23
Almost completely saussuritized feldspar partly replaced by quartz. Loc. 1995 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 81

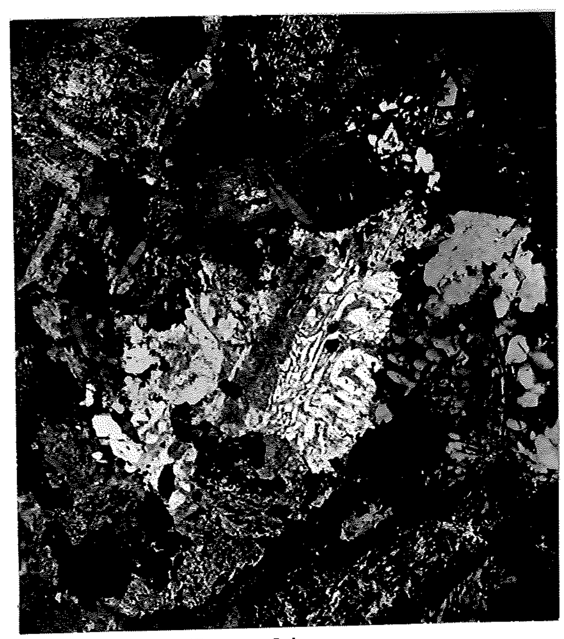


Fig. 24
Almost completely saussuritized feldspar partly replaced by quartz. Loc. 1995 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 81

Fig. 25
Almost completely saussuritized and kaolinized feldspar partly replaced by quartz. Loc. 2195 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 85

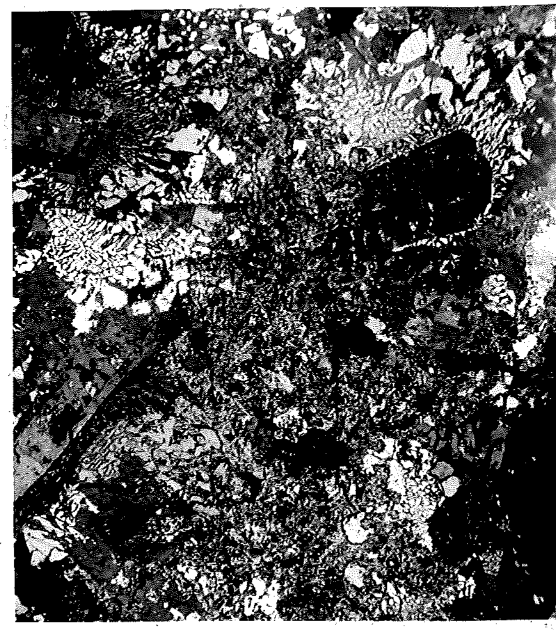


Fig. 26
Albite partly replaced by quartz. Loc. 2775 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 86

Fig. 27
Albite partly replaced by quartz. Loc. 2875 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 87

Fig. 28
Albite partly replaced by quartz. Loc. 2975 ft. S.E. from Sec. 67. X 45, X-nicols.
Sec. No. 88

Fig 29
Albite and orthoclase partly replaced by quartz. Loc. 3075 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 89

Fig. 30
Albite partly replaced by quartz. Loc. 3150 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 90

Fig. 31
Albite partly replaced by quartz. Loc. 4150 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 91

Fig. 32
Albite partly replaced by quartz. Loc. 6650 ft. S.E. from Sec. 67. X 45, X-nicols.
Sec. No. 92

Fig. 33
Albite partly replaced by quartz.
Loc. 9100 ft. S.E. from Sec. 67.
X 45, X-nicols.
Sec. No. 93

Fig. 34
Albite partly replaced by quartz.
Loc. 10,300 ft. S.E. from Sec. 67.
X 45, X-nicols.
Sec. No. 94

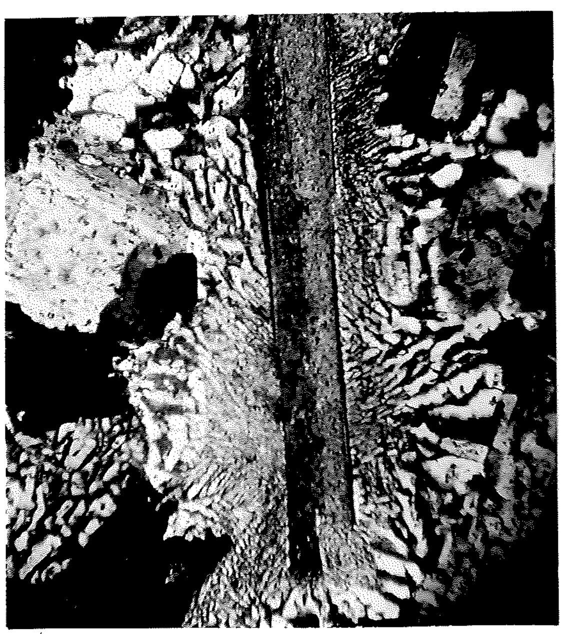


Fig. 35
Albite partly replaced by quartz.
Loc. 10,350 ft. S.E. from Sec. 67.
X 45, X-nicols.
Sec. No. 95

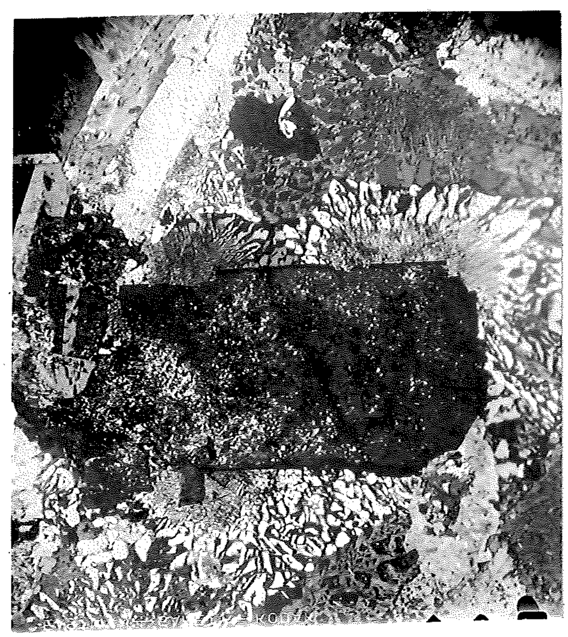


Fig. 36
Orthoclase, containing remnants of albite, partly replaced by quartz. Loc. 10,350 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 95

Fig. 37
Albite partly replaced by quartz. Note small remnant of albite in center of fret. Loc. 10,400 ft. S.E. from Sec. 67. X 45, X-nicols.
Sec. No. 96

Fig. 38
Orthoclase, containing patches of albite, partly replaced by quartz. Loc. 10,950 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 97

Fig. 39
Albite and orthoclase partly replaced by quartz. Loc. 11,025 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 99

Fig. 40
Albite and orthoclase partly replaced by quartz. Loc. 11,125 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 100

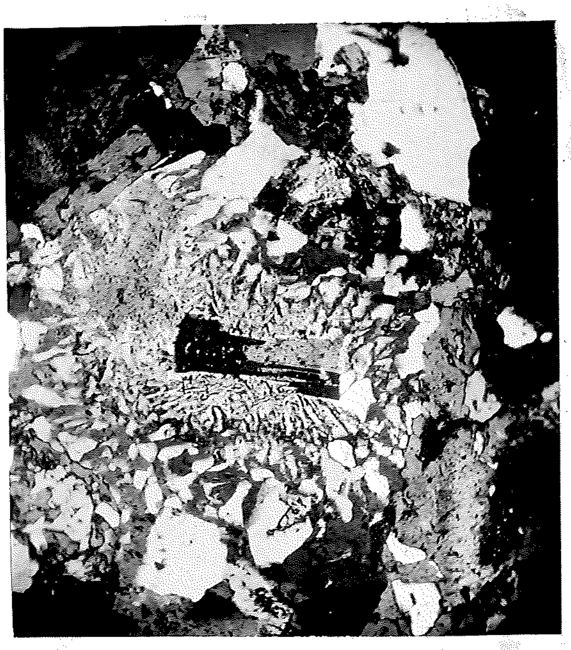


Fig. 41
Albite and orthoclase partly replaced by quartz. Loc. 11,200 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 101

Fig. 42
Albite and orthoclase partly replaced by quartz. Loc. 11,725 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 102

Fig. 43
Anorthoclase partly replaced by quartz. Note euhedral form of fret. Loc. 11,875 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 103

Fig. 44
Albite in feldspathized tuff partly replaced by quartz. Loc. 11,950 ft. S.E. from Sec. 67. X $20\frac{1}{2}$, X-nicols.
Sec. No. 104

Fig. 45
Saussuritized plagioclase partly replaced by quartz. Loc. N.E. corner lot 12, con. III, Wisner twp., 1500 feet below base of norite. X $20\frac{1}{2}$, X-nicols.
Sec. No. 419

Fig. 46
Albite partly replaced by quartz. Loc. 3000 ft. from base of norite, lot 1, con. III, Wisner twp. X $20\frac{1}{2}$, X-nicols.
Sec. No. 2185

Fig. 47
Anorthoclase partly replaced by quartz. Loc. 3000 ft. from base of norite, lot 1, con. III, Wisner twp. X $20\frac{1}{2}$, X-nicols.
Sec. No. 2185

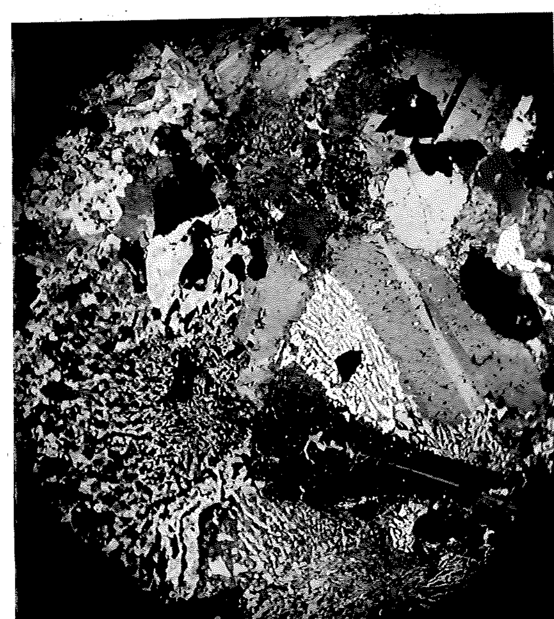


Fig. 48
Albite partly replaced by quartz. Loc. 6100 ft. from base of norite, lot 1, con. III, Wisner twp.
Sec. No. 2186

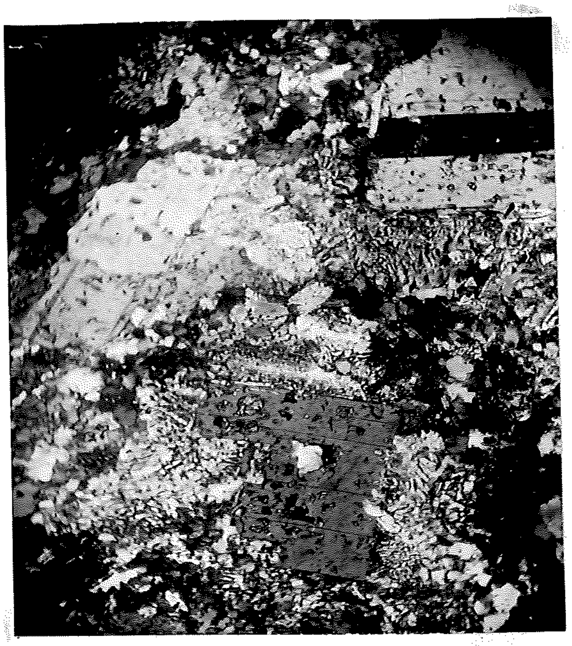


Fig. 53
Feldspathized tuff partly replaced by quartz. Loc. lot 2, con. II, Rayside twp. X 45, X-nicols.
Sec. No. 245

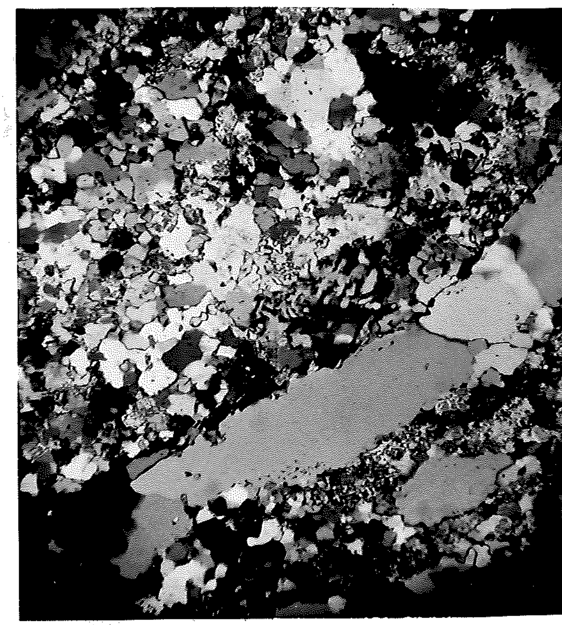


Fig. 54
Feldspar in feldspathic quartzite fragment in volcanic breccia partly replaced by quartz. Loc. lot 3, con. III, Rayside. X 45, X-nicols.
Sec. No. 246

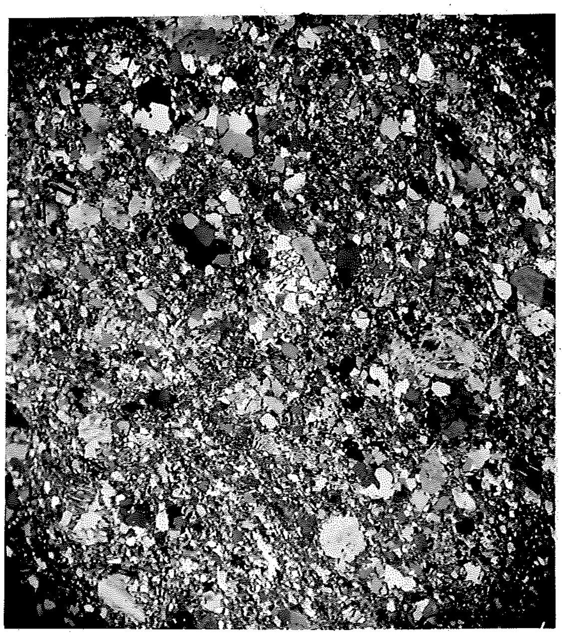


Fig. 55
Hornfelsic matrix in tuff partly replaced by quartz. Loc. lot 3, con. III, Rayside twp. X $20\frac{1}{2}$, X-nicols.
Sec. No. 247

Fig. 56
Feldspar in feldspathic quartzite fragment in volcanic breccia partly replaced by quartz. Loc. lot 3, con. II, Rayside twp. X $20\frac{1}{2}$ X-nicols. Sec. No. 362

Fig. 57
Micrographic texture, clinozoisite in partly altered augite. Loc. 6100 ft. from base of norite, lot 1, con. III, Wisner twp. X 45, X-nicols.
Sec. No. 2186

Fig. 58
Same photomicrograph as Fig. 57, X-45, plain pol. light.

Fig. 59
Micrographic intergrowth of clinochlore and orthoclase in sulphides, (black) pyrrhotite, pentlandite, and chalcopyrite. Loc. Falconbridge mine. X 45, plain pol. light
Sec. No. 7

Fig. 60
Micrographic intergrowth of saussuritized feldspar and magnetite. Solid black consists of pyrrhotite. Loc. Murray mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 378

Critical Discussion of the Several Hypotheses in Relation to the Field and Petrographic Evidence Regarding the Emplacement of the Sudbury Intrusive

Coleman's Gravitative Separation Theory

The theory of gravitative differentiation, as developed by Coleman and accepted by many geologists, does not take into consideration the relative positions of the norite, transition zone, and micropegmatite. Only the upper micropegmatite layer would now be visible if, as they believe, the present shape of the basin is the result of an ebb in the magma chamber, causing a collapse of the floor underlying the intrusive, before gravitative separation took place.

Furthermore the statements that there is a regular composition gradient upward from the base of the norite to the top of the micropegmatite have been disproved by both chemical and mineralogical analyses. It has been proved that the rock with the highest specific gravity does not occur at the base of the norite but near the top of it. Careful studies of both the micropegmatite and the norite have failed to reveal any sign of an upward composition gradient in either of these rock types. The only suites of rock specimens that show a gradational composition are those which were collected, along some traverses, across the transition zone.

Knight's Theory of the Intrusive as a Ring Dike

No one has offered any additional evidence to support Knight's suggestion (38, 1917, pp. 115-122) that the Sudbury basin was formed by a great down faulted block, and that the norite-micropegmatite was injected around the faulted block. Although by reference (40) he compared magmatic differentiation in the Sudbury intrusive with that in the Nipissing diabase sills, he offered no explanation as to how this might have taken place in the dike form of the Sudbury intrusive.

He also presented evidence that failed to support Coleman's theory of magmatic differentiation. He proved, by chemical analyses of suites of specimens collected across the intrusive, that there is not a gradual transition from basic to acid rock. By the same method he confirmed Harker's (30) observation that there is no indication of a regular composition gradient in either the norite or micropegmatite, considered separately.

At a number of localities, along the South range, the dip of the contact at the base of the norite with the footwall rocks varies from nearly vertical to steep angles away from the center of the basin. Knight based his theory on the belief that these steep and reversed dips were on intrusive contacts; but later studies by the geological staff of the International Nickel Company have proved that these exceptional structures are the result of post-intrusive faulting.

Phemister's Theory of Two Separate Intrusions

T. C. Phemister (42) made quantitative mineral analyses of specimens which he had collected along eleven traverses across the Sudbury intrusive. The following is a brief summary of his field and laboratory observations:

1. As the micropegmatite is approached, the feldspar in the norite becomes altered to a mass consisting of epidote and white mica. Also, near the micropegmatite, there is a development of hornblende in the norite, and an introduction of quartz and alkali feldspar.

2. There is no sharp contact between the norite and micropegmatite, except on the shore of the south-central part of Whitson Lake, but the junction of the norite and micropegmatite, generally, has the characteristics of a contact and not those of a gradation between phases of one intrusive.

3. At the southwest corner of the basin the micropegmatite has been forced into the crust apart from the norite.

4. North of Creighton mine a dike of micropegmatite, about a foot in width, was found intruding the norite.

Based principally on the above observations, Phemister attempted to prove that the micropegmatite and the norite had been emplaced as separate intrusions. He attributed the absence, except in a single case, of a distinct contact between these two rock types to the elapse of a short time interval between the two intrusions. He believed that the intrusion and solidification of the norite were closely followed by the intrusion of the micropegmatite, while the former was still hot, and that the alteration of the minerals in the zone between the two rock types is the result of contact metamorphic action.

The definite contact of norite and micropegmatite which Phemister reported he had discovered along the south shore of Whitson Lake could not be located by the writer, and Collins (18) states:

> Although we crossed from norite to micropegmatite at intervals of 500 and 1000 feet around the entire nickel basin, we found everywhere between them, where the drift cover permitted observation, a transitional zone 250 to 800 feet wide.

Phemister's observation that at the southwest corner of the basin "the micropegmatite has been forced into the crust apart from the norite" fails to recognize the effects of the Cameron Creek fault which, at the above locality, shows a horizontal displacement of several thousand feet.

The writer does not believe that the intense alteration of all the primary minerals in the transition zone would result from the emplacement of an overlying intrusive and, although he has examined many exposures of this transition zone, he has found no evidence to indicate that an intrusive contact exists between the norite and micropegmatite.

Bain's Theory of Assimilation by the Norite of the Overlying Rocks

G. W. Bain (1) attempted to prove that the micropegmatite of the Sudbury intrusive is the result of assimilation, by the original magma, of an amount of rock equivalent to two-thirds of its original volume, and possibly as much as two to three times that amount.

Bain's theory never gained any support, since his calculations were based partly on published analyses of samples that had been collected by previous workers from random points along the South range and partly on analyses of samples that had been collected from a gabbro mass north of Spanish River which is not a part of the norite-micropegmatite that forms the outer rim of Sudbury basin.

Collins' Theory of Magmatic Differentiation

Collins, with the assistance of several experienced geologists, spent the period 1928-1932 in studying and re-mapping the entire Sudbury intrusive and the "offsets." In addition to the numerous chemical and mineralogical analyses that had been published by former workers, the series of papers prepared by Collins (18) contain much new material.

After clearly pointing out the inadequacies of the theory of magmatic segregation by the process of fractional crystallization, to account for the distribution of titaniferous magnetite, apatite, and in some degree pyroxene, he stated his belief that the intrusive had differentiated as immiscible liquid fractions in a common magma. By plotting curves showing the variation in specific gravity along eight traverses across the intrusive, he concluded that the density of the norite portion of the intrusive varies in a fairly characteristic way from about 2.82 to a peak of 2.99 - 3.04 near the transition zone. He suggested that the density interval between 2.70 and 2.85 was the governing factor in separating norite, transition rock, and micropegmatite. He concluded that this density interval acted as a screen, which permitted any material with a specific gravity of 2.85 or more to pass downward but held up anything with a specific gravity of 2.70 or less, and caught in its meshes anything between these two figures.

The writer has never been able to follow the above reasoning, since the material having the highest specific gravity is found at the top of the norite, and not at the base, where it would be if the process suggested by Collins had been in operation.

Finally, he compared the Sudbury intrusive with the Bushveld Complex, in that the zone rich in titaniferous magnetite in the former occurs in the same relative position as the titaniferous iron ore layers in the latter. But even this analogy fails to account for the relative positions of the three types of rocks in the Sudbury intrusive.

Buddington (5) in reviewing Collins' articles stated:

> The final conclusion that both norite and micropegmatite differentiated as liquids from a common magma is not in accord with prevailing opinion; but, as several geologists have pointed out, there is at present no really positive experimental proof that granitic magmas relatively rich in water can not be immiscible with basic types, although the present data are in general unfavorable to it.

The Writer's Theory Regarding Emplacement of Norite and Formation of Micropegmatite

The Sudbury intrusive has the shape of a huge, irregular funnel; Salomon (46) has given the name "Ethmolith" (literally funnel-rock) to this form. The writer believes that this shape was mostly controlled by a synclinal structure that had been developed before the emplacement of the intrusive.

Petrographic evidence suggests that much of the alteration in the norite is the result of deuteric processes; but none of this type of evidence indicates that the micropegmatite is the result of primary crystallization from a liquid silicate melt. The relict textures seen in the thin-sections and the relict structures seen in the field suggest to the writer that a large part of the micropegmatite was formed from the lowest formation of the Whitewater series, by the process of metasomatism, and that the active agencies of this process were solutions and gases that originated from the same source as the norite.

IV

GENERAL OUTLINE OF CHARACTER AND DISTRIBUTION OF METAMORPHIC ROCKS IN THE SUDBURY AREA

Practically all the rocks in the Sudbury area show signs of dynamic regional metamorphism, which varies with their mineralogical and chemical composition; the least mineralogical and textural changes are found in the highly siliceous rocks, and the greatest changes of this character occurred in the more basic rocks. Added to this regional metamorphism, the effects of various types of more intense metamorphism can be recognized in certain localized areas.

Specimens of Metamorphosed Rocks Collected in the Sudbury Area

There is considerable variation in the mineralogical composition of rocks from a single formation, so the following descriptions may differ somewhat from those, of the same classification, collected from different localities.

Mississagi Quartzite (north shore Lake Panache). This rock is composed mostly of medium-grained quartz and lesser amounts of orthoclase and microcline, embedded in a matrix of finer-grained quartz and feldspar, and minor amounts of sericite and chlorite.

Bruce Conglomerate (north shore Lake Panache). This rock contains boulders up to more than a foot in diameter in a matrix which consists of coarse grains of quartz, orthoclase, and plagioclase that are embedded in a matte of micas and carbonate.

Bruce Limestone (north shore Lake Panache). This specimen consists of scattered grains of quartz in a partly recrystallized carbonate.

Espanola Graywacke (north shore Lake Panache). This specimen consists of medium-grained quartz, orthoclase, and plagioclase in a matrix of carbonate, white mica, and chlorite.

McKim Graywacke (Garson gravel pit on boundary of Garson-Neelon townships). This specimen consists of a hornsfelsic matrix of quartz, feldspar, mica, and opaque material, with scattered porphyroblasts of quartz and sulphides.

Serpent Quartzite (north shore Lake Panache). This specimen is composed of quartz and feldspar grains, up to one-half millimeter in diameter, in a matrix of fine-grained recrystallized quartz and feldspar, and shreds of biotite and sericite, and streaks of chlorite. Some almost euhedral porphyroblasts of feldspar, up to two millimeters long, enclose crowded grains of recrystallized quartz and sericite in a sieve structure.

Ramsay Lake Conglomerate-Matrix (Garson gravel pit, boundary Garson-Neely townships). This specimen is composed of approximately 50 per cent quartz and the remainder consists of albite, perthite, and microcline; there is a small amount of interstitial sericite and chlorite.

Copper Cliff Rhyolite (lot 10, con. IV, McKim twp.). This specimen is composed of fine-grained recrystallized quartz and feldspar with a little interstitial epidote and clinozoisite; this matrix contains a few scattered "eyes" of recrystallized quartz.

Another specimen of Copper Cliff Rhyolite that was taken in lot 11, con. V, McKim township, is composed of recrystallized quartz, albite, and orthoclase, with considerable amounts of green and brown biotite, clinozoisite, hornblende, and glaucophane, and lesser amounts of leucoxene and zircon. The hornblende and glaucophane porphyroblasts enclose some of the minerals of the matrix.

Frood Series Amphibolite (lot 11, con. V, McKim twp.). This specimen is composed mostly of porphyroblasts of amphiboles (hornblende and glaucophane), some of which enclose a little recrystallized quartz and feldspar; there are also a few patches and streaks made up of recrystallized quartz and feldspar, patches of biotite, shreds of chlorite, and scattered grains of ilmentite that have rims of leucoxene.

Frood Series Quartz-Mica Schist (lot 11, con. IV, McKim twp.). This specimen is composed of recrystallized grains of quartz and feldspar, with interstitial sericite, muscovite, and chlorite; a large dense patch of sericite with some included muscovite and chlorite may be the alteration products of staurolite.

Elsie Mountain Series Altered Gabbro (lot 5, con. II, Blezard twp.). A specimen taken from this rock is composed of a matrix of sugary-grained plagioclase, diopside, and hypersthene in which occur large porphyroblasts of hornblende that enclose patches and grains of the matrix material.

A large area of saussurite-gabbro and saussurite-norite occurs in Drury and Denison townships; the following four specimens were collected across a zone approximately 400 feet wide northeast of Crean Hill mine.

Saussurite-Norite (lot 4, con. V, Denison twp.). The specimen taken from the base of the zone is composed of large crystals of labradorite that are partly altered to albite, microcline, clinozoisite, epidote, zoisite, and carbonate; the dark minerals consist of chlorite, biotite, ilmentite, and leucoxene.

The specimen taken approximately 200 feet from the base is composed of fine-grained mass of completely recrystallized minerals that consist of albite, epidote, clinozoisite, leucoxene, actinolite, chlorite, biotite, and quartz.

The specimen taken approximately 300 feet from the base of the zone is similar to the one above but contains more or less altered mafic minerals; a little residual augite still remains.

A specimen taken from a drill core approximately 400 feet from the base of the zone is composed of residuals of labradorite, most of which has been altered to albite, epidote, zoisite, and clinozoisite; the mafic minerals consist of tremolite and actinolite, and biotite; the quartz is strained and recrystallized, and a fine veinlet of quartz-carbonate cuts across the section.

Saussurite-Gabbro (lot 3, con. V, Drury twp.). This specimen is composed of patches of fine-grained recrystallized feldspar, epidote, zoisite, clinozoisite, and strained and recrystallized quartz, and patches and streaks of chlorite, epidote, and secondary amphiboles.

Michener (38), in the following Table 16, compared the chemical analysis of a specimen of saussurite-norite, taken from this area, in the early stage of alteration, with the average of fifteen analyses of the norite specimens collected by W. H. Collins across the Creighton section. In Table 17 is presented his comparison of the chemical analysis of a specimen of saussurite-gabbro, taken from this area, in an advanced stage of alteration, with the average of 184 gabbros from Europe and America (34).

Frood Type Breccia. The Frood type intrusive breccia, which has sometimes been called "crush-conglomerate," is known to be widely distributed over the area south of Sudbury basin, and recent work has proved that similar breccias occur in the footwall granite and gneiss of the North range.

TABLE 16

COMPARISON OF CHEMICAL ANALYSES OF SAUSSURITE-NORITE AND AVERAGE NORITE CREIGHTON SECTION

	Saussurite-Norite 7534-B	Average Norite Creighton Section	Limits Between 15 Analyses Creighton Section
SiO_2	52.58	54.41	51.34 - 56.60
Al_2O_3	18.72	17.61	16.33 - 20.18
Fe_2O_3	2.15	1.17	0.65 - 3.55
FeO	7.16	6.97	5.63 - 8.19
CaO	8.41	7.89	6.55 - 8.87
MgO	6.82	6.01	0.69 - 6.66
Na_2O) K_2O)	3.62	3.71	2.46 - 4.69
H_2O	2.00	0.81	0.55 - 3.59
CO_2	0.22	0.12	0.07 - 0.40
	99.68	98.70	

TABLE 17

COMPARISON OF CHEMICAL ANALYSES OF SAUSSURITE-GABBRO WITH AVERAGE GABBRO

	Saussurite-Gabbro Drury Township	Average Gabbro Europe and America
SiO_2	49.68	49.25
Al_2O_3	22.02	17.49
Fe_2O_3	1.86	3.76
FeO	5.62	5.96
CaO	8.06	10.61
MgO	5.34	6.61
Na_2O - K_2O	4.05	3.59
H_2O	1.25	1.59
CO_2	0.21	0.09
	98.09	98.95

TABLE 18

COMPARISON OF THE MINERAL COMPOSITION OF THE HOST ROCKS WITH THAT OF THE BRECCIA MATRIX MATERIAL (45)

Rock	Minerals in the Unaltered Rock	Minerals in the Matrix	
		Inherited	Introduced
Copper Cliff Rhyolite	perthite microcline green biotite	perthite microcline quartz	oligoclase brown biotite quartz clinozoisite epidote
McKim Graywacke	andesine white mica quartz zircon (?)	andesine white mica quartz zircon	oligoclase white mica biotite quartz scapolite carbonate sulphide clinozoisite epidote
Ramsay Lake Conglomeritic Grit	oligoclase andesine white mica quartz grit quartz grains	oligoclase andesine white mica quartz grit quartz grains	oligoclase biotite white mica quartz carbon-ate sulphide clinozoisite epidote
Mississagi Quartzite	oligoclase andesine white mica biotite quartz zircon	oligoclase andesine white mica biotite quartz zircon	oligoclase biotite quartz carbonate sulphide clinozoisite epidote
Sudbury Gabbro	labradorite bytownite hornblende biotite quartz magnetite	quartz hornblende magnetite	actinolite antigorite white mica quartz sulphide clinozoisite epidote

Following his comparison (Table 18) of the mineral composition of the host rocks with that of the breccia matrix material, Robson (45) comments:

> The presence of the introduced minerals, micas, feldspars, scapolite, carbonate, and pyrrhotite indicates that the solutions entering the breccias must have contained sodium, calcium, sulphur, carbon dioxide and chlorine. Spectographic analyses show that nickel, selenium, and vanadium were also present in minor amounts. The minerals introduced indicate hydrothermal conditions.
>
> No doubt the solutions were derived from the magma from which some of the late igneous rocks of the area have come. The similarity of rock-breccia to ore-breccia and their occurrence in the rocks of the same age suggest the possibility of a common origin.

Onaping Volcanics. Three distinct stages of metamorphism have been recognized in this formation, two of which are directly related to the Sudbury intrusive. The first stage produced a hornfels which grades from a fine-grained phase, resembling the tuffaceous matrix, at the outer margin of the metamorphic aureole, to a medium-grained phase resembling, in texture and mineral composition, the micropegmatite with which it is in contact at the inner margin. The principal minerals consist of quartz, albite, orthoclase, and perthite, with minor amounts of chlorite, epidote, hornblende, and leucoxene. The second stage produced large and small masses and veinlets, consisting principally of albite, quartz, and orthoclase; the texture varies from fine to medium-grained. The third stage resulted in the replacement of extensive areas of fine-grained tuff by quartz and carbonate.

Onwatin Slate. The principal metamorphic effect seen in this rock is the well developed cleavage. It is composed principally of black, opaque carbonaceous material with minor amounts of quartz, sericite, and chlorite.

Chelmsford Sandstone. In addition to weak cementation, large oval concretions, composed of the carbonates of iron and calcium, have been developed in many areas of this formation.

The Sudbury Intrusive. The metamorphic effects, in the micropegmatite, as seen and interpreted by the writer, have been described in detail under the heading "Micropegmatite." Various types of alteration are found in the norite; these range from those that are generally accepted as deuteric effects of a cooling magma to some that appear to be the result of localized dynamic forces, and others that show the effects of either thermal or hydrothermal agencies.

V

THE SUDBURY ORE DEPOSITS

General Description

The copper-nickel deposits of the Sudbury area have been divided into two general types: marginal and offset deposits.

The marginal deposits are found adjacent to the contact of the norite and the footwall rocks and usually consist of a series of orebodies that occur along faulted, sheared, or brecciated zones within both the norite and the footwall rocks. The shape of the orebodies varies in detail; some are tabular, some are lenticular, and others are pipe-like in form. The size of these deposits varies from those that have produced a few thousand tons to those that have produced many millions of tons of ore. The largest of these are Creighton, Garson, Levack, Falconbridge, and Crean Hill.

The offset deposits are those that are found in dike-like intrusive bodies of quartz diorite and Frood breccia, which occur outside the nickel intrusive. These dikes carry many fragments of older rocks which vary from microscopic sizes to masses more than 100 feet in diameter. The shape of the ore deposits found in these offsets is as variable as that found in the marginal deposits. The size of the individual orebodies varies from rather small lenses, such as have been developed in the Foy offset, to that being mined at Frood-Stobie mine, which up to October 1, 1945, had produced more than 60,000,000 tons of ore, and still contains the bulk of the ore reserves of this district.

Mineralogy

The Sudbury copper-nickel ores have been divided into the following four types: disseminated, massive disseminated, massive sulphide, and breccia sulphide.

The disseminated ore consists of spots and patches of sulphides that vary from microscopic sizes to more than an inch in diameter. These sulphides are found in all the footwall rocks as well as in the norite and quartz diorite; the amounts vary with the different rock types, but the minerals present and their proportions are independent of the nature of the host rock.

Usually the spots and patches consist of pyrrhotite with ragged inclusions of magnetite and gangue minerals, and crystals and veinlets of pentlandite; chalcopyrite, in varying amounts, occurs as veinlets cutting both pyrrhotite and pentlandite, and as fine-grained disseminations around kernels of pyrrhotite. The less common minerals such as nickel arsenides, galena, sphalerite, silver, gold, and the platinum group minerals, are often found with these fine-textured phases.

The disseminated ore varies in sulphide content from a fraction of one per cent, where the sulphide spots and patches are spaced widely apart, to nearly 100 per cent where the ore is classified as massive disseminated. Except for some marked local variations, the relative proportions of pentlandite, pyrrhotite, and chalcopyrite appear to be fairly constant in the disseminated ores of all grades. The texture of this type varies with the texture of the host rock.

Massive sulphide ore invariably contains inclusions of nearly every pre-ore rock in the vicinity. These vary in size from a fraction of an inch to fragments many feet in diameter. The texture of this type of ore is coarser than that of the disseminated ore. This has been attributed to the textual differences of the rocks that each type replaced.

Breccia sulphide ore is a type in which large and small fragments of gangue rocks, free from sulphide disseminations, are enclosed in a matrix of massive sulphide minerals.

Except for a difference in degree of concentration of metallic minerals, the mineralogy of all these types of ores is essentially the same.

Michener (39) has contributed the latest and most detailed information relating to the mineralogy of these ores, and the following notes have been taken from his dissertation:

> In general the mineralogy is more complex than the literature would lead one to believe. The three sulphides: pyrrhotite, chalcopyrite, and pentlandite are present in all the ores but under special circumstances and especially in the offset deposits, a considerable number of other primary metallic minerals are to be found. Twenty-nine primary minerals were studied. Of these twenty are ore minerals. The nickel minerals include magnetic pyrrhotite, non-magnetic pyrrhotite, pentlandite, silver-bearing pentlandite, cobalt-bearing pentlandite, maucherite, niccolite, gersdorffite, NiBiS, and pyrite. Of these, NiBiS is a new nickel mineral and two others are new varieties of pentlandite. The copper minerals include chalcopyrite, cubanite, tetrahedrite, and bornite. The platinum group minerals are sperrylite, $PdBi_3$, and Pd_2Bi_3, two of which are new palladium minerals. The minerals of gold and silver are native gold, electrum, hessite and silver-bearing pentlandite. Tellurium minerals are hessite and tetradymite. Base metals present in small quantities and represented by various groups of minerals include bismuth, cobalt, lead, zinc, tin, cadmium, arsenic, antimony, and titanium.

Possible Mechanisms of Emplacement of the Sudbury Copper-Nickel Ores

To account for the Sudbury copper-nickel deposits, the following theories have been proposed.

1. Magmatic differentiation in situ from the Sudbury intrusive, by the action of gravity on an immiscible silicate-

sulphide melt. This theory has been supported by Barlow (2), Coleman (11, 14, 15), Moore and Walker (15), Collins (18), and many other geologists.

2. Deposition of sulphides by hydrothermal agencies. This theory has been supported by Dickson (25), Campbell and Knight (8), Wandke and Hoffman (49), Phemister (42), and many others.

3. Deposition of sulphides at a late magmatic stage, by the action of mineralizers. This theory was proposed by Tolman and Rogers (47).

4. Deposition by intrusion of sulphides which had differentiated from the silicates in the magmatic reservoir, and not in the chamber of the Sudbury intrusive. This theory was proposed by Howe (31).

5. Deposition of sulphides by progressive mineralization that embraces parts of all the theories advanced above. This idea was proposed by Bateman (3).

Evidence that these copper-nickel ores were emplaced a considerable time after the norite had solidified can be seen at all the producing mines. The writer is convinced that pre-ore structures such as faulting, shearing, and brecciation, all of which involved, in part, the solidified norite as well as the older footwall rocks, constitute the structural framework that controlled the deposition of these ores.

That the sulphides replaced earlier silicate minerals is suggested by the similarity of the textures of the sulphides, to those of the host rocks in which they occur. As early as 1905, Coleman (14, p. 52) noted this fact; in describing the texture of the ore on the dump at Murray mine he states that ". . . as at most other nickel mines in the district, the ore [is] in coarse grains when the rock is coarse-grained, and vice-versa."

Description of the Various Mines in the Sudbury Area

Creighton Mine

The Creighton mine is situated about 11 miles west of Sudbury. The ore deposits lie in a distinct embayment in the footwall rocks; in addition to norite, this embayment is partly filled with an irregular mass of breccia, somewhat similar to the quartz diorite "offset" rock, even to the extent of having a thin massive marginal phase containing no fragments of older rocks. The contact of this breccia with the norite is not always sharp; there is often an actual gradation, over a few inches, from the breccia containing sulphides to coarse norite free from sulphides. Large and small fragments of normal gray norite are found within the breccia.

In addition to granite, the principal footwall rock found in this area, various other types such as quartzite, arkose, gabbro, and greenstone are in contact with the norite and breccia on the south side of the embayment. On the southwest side, the strike of these footwall rocks is parallel to their contact with the norite, but on the east side of the bay they are truncated by the norite. Since their dip to the northeast is steeper than that of their contact with the norite, the different members of this series progressively come into contact with the norite with depth.

Most of the original orebody, which extended from the surface to the 28-level, occurred in the footwall rocks. The length of this orebody ranged from 500 to 1,000 feet, and the width varied from 50 to 300 feet. Its average dip was 45 degrees west. The above description of a relatively simple structure can not be applied to the orebodies that are now being mined from this deposit.

A system of faulting and shearing, having a northeast-southwest strike and a northwest pitch, intersects and cuts the norite and breccia of the bay into thin slabs, and terminates in the footwall rocks as brecciation. The distribution of the sulphides is definitely controlled by these structures. Massive sulphides occur along the shears, as the matrix of a breccia composed of fragments of all types of footwall rocks and norite, and as veins in disseminated ore and footwall rocks. The disseminated ore is confined to the noritic rock, and, generally, decreases in grade with the increase in distance from the above structures. A series of massive copper sulphide

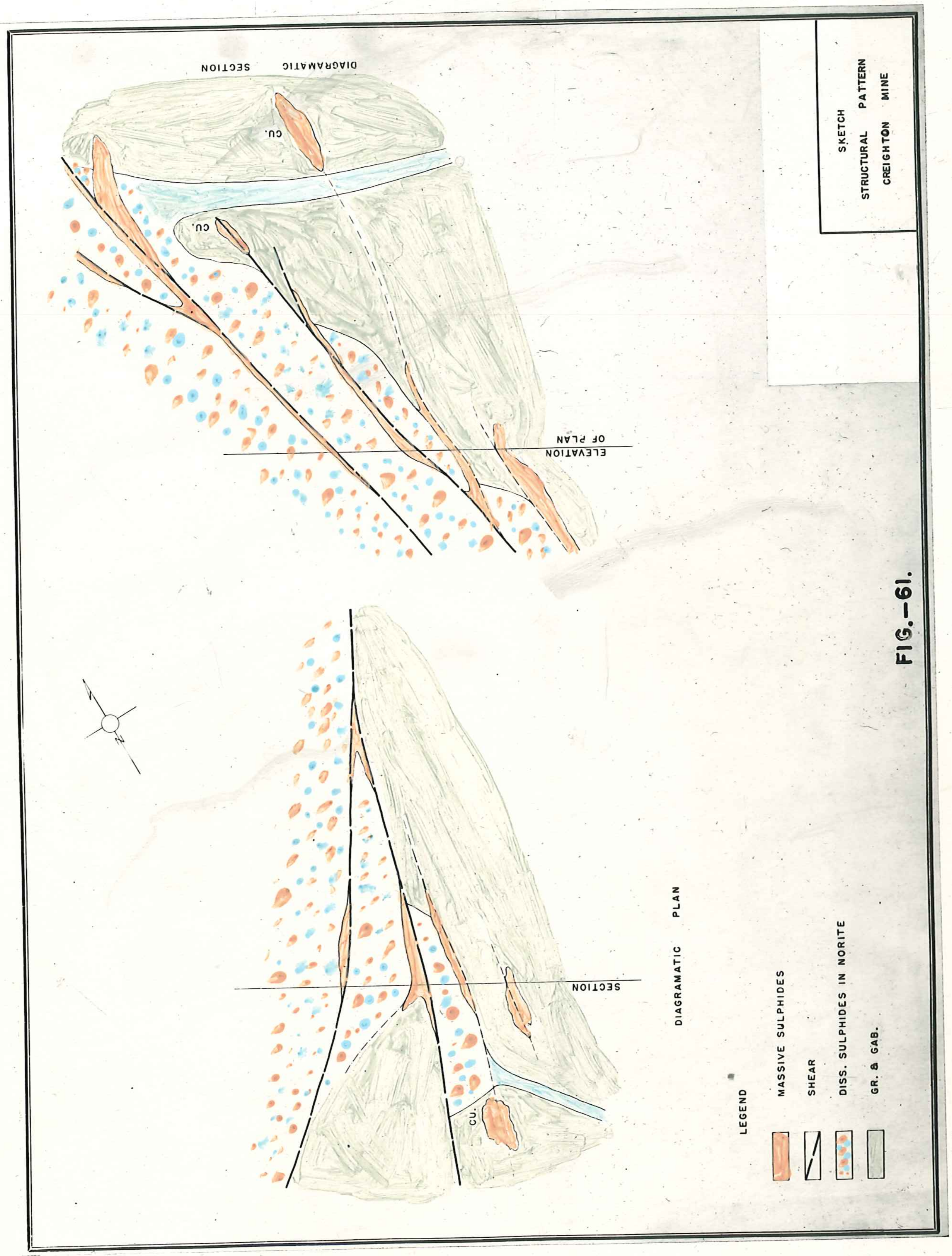

SKETCH
STRUCTURAL PATTERN
CREIGHTON MINE
DIAGRAMATIC SECTION
CU.
CU.
ELEVATION OF PLAN
DIAGRAMATIC PLAN
SECTION
CU.
N
LEGEND
MASSIVE SULPHIDES
SHEAR
DISS. SULPHIDES IN NORITE
GR. & GAB.

FIG.—61.

orebodies occur in zones of brecciation in the footwall rocks along the projected planes of shearing.

The ratio of pyrrhotite to pentlandite is 2 to 1 for the copper orebodies, and 3.4 to 1 for all other ore. The approximate ratio of copper to nickel is 3 to 1 for the copper orebodies and 0.5 to 1 for ordinary massive ore, and 0.7 to 1 for the disseminated ore.

Frood Mine

The Frood mine, the largest in the district and having the simplest structure, is the only offset deposit being mined, by the International Nickel Company, at the present time. It is situated about one mile south of the main norite mass and about two miles north of the city of Sudbury.

The offset in which this deposit occurs is composed of a series of lenses, or fragments, of quartz diorite in Frood breccia. The orebody strikes northeast-southwest and dips about 75 degrees to the northwest. It is 3,500 feet long and averages 85 feet in width at the 1,800-foot level, but above the 1,400 level the hangingwall steepens so that the width increases to 800 feet at the surface.

The explanation of the relation between the quartz diorite "lenses" and the Frood breccia is still controversial. One feature that has made correct interpretation of relation difficult is the fact that the "lenses," of quartz diorite, which form the cores of the orebodies, contain inclusions, thereby causing this rock to be confused with the Frood breccia. These inclusions, which are of varied sizes up to 100 feet or more in length, exhibit the same outline as the fragments in the Frood breccia; many are well-rounded, the majority are subangular to rounded, and a few have sharp angular edges. This quartz diorite breccia differs from the Frood breccia in the following details: most of the inclusions are of the same rock; a gray gabbro in various stages of alteration, from a fresh quartz pyroxene gabbro to an end product composed mainly of tremolite and products of feldspar alteration, such as zoisite and sericite. These gabbro inclusions are currently being correlated by the mine geologists with the peridotite at Levack, i.e., a product of the main norite mass. These inclusions are practically unmineralized, and contacts between them and the quartz diorite are always sharp.

The ore is classified as disseminated ore, breccia ore, and massive sulphide ore. The greater part of the orebody is composed of disseminated ore in quartz diorite, the sulphide content of which varies widely, from less than one per cent to nearly 100 per cent. The essential minerals are pyrrhotite, chalcopyrite, and pentlandite; the copper-nickel ratio is about 1:1, and the pyrrhotite-pentlandite ratio is about 5.4:1.

The breccia ore and the massive sulphide ore occur as discontinuous shells or envelopes around cores or groups of cores of disseminated ore, and their proportions progressively increase with depth. These types are characterized by an irregularity of texture which appears to have been inherited from the host rocks in which they occur. The breccia ore consists of remnants of schist and partly rounded fragments of more resistant rocks in a matrix composed of a mixture of fine-grained sulphides and residual silicate minerals from the Frood breccia matrix. The essential minerals are pyrrhotite, chalcopyrite, and pentlandite, with galena and arsenides and sulpharsenides of nickel as accessories. The ratio of copper to nickel is about 1:1, and the pyrrhotite-pentlandite ratio is about 5.4:1.

The massive sulphides ore occurs with the country rocks of the walls, and appears to have inherited the textures and structures of the host rocks with which they are found. At the walls of an orebody and parallel to them, no matter how irregular they may be, there is usually a slight zoning in the ore across widths of a few inches up to many feet. The massive pyrrhotite of the general orebody gives way to practically pure chalcopyrite, followed by a band of niccolite and then by a margin of various white cobalt-nickel arsenides. The adjacent wallrock, no matter what its composition, is generally intensely altered, over a narrow width, to amphibole, biotite, and garnet. This alteration may be present whether or not the arsenides occur at the contact. In other places, quartz and

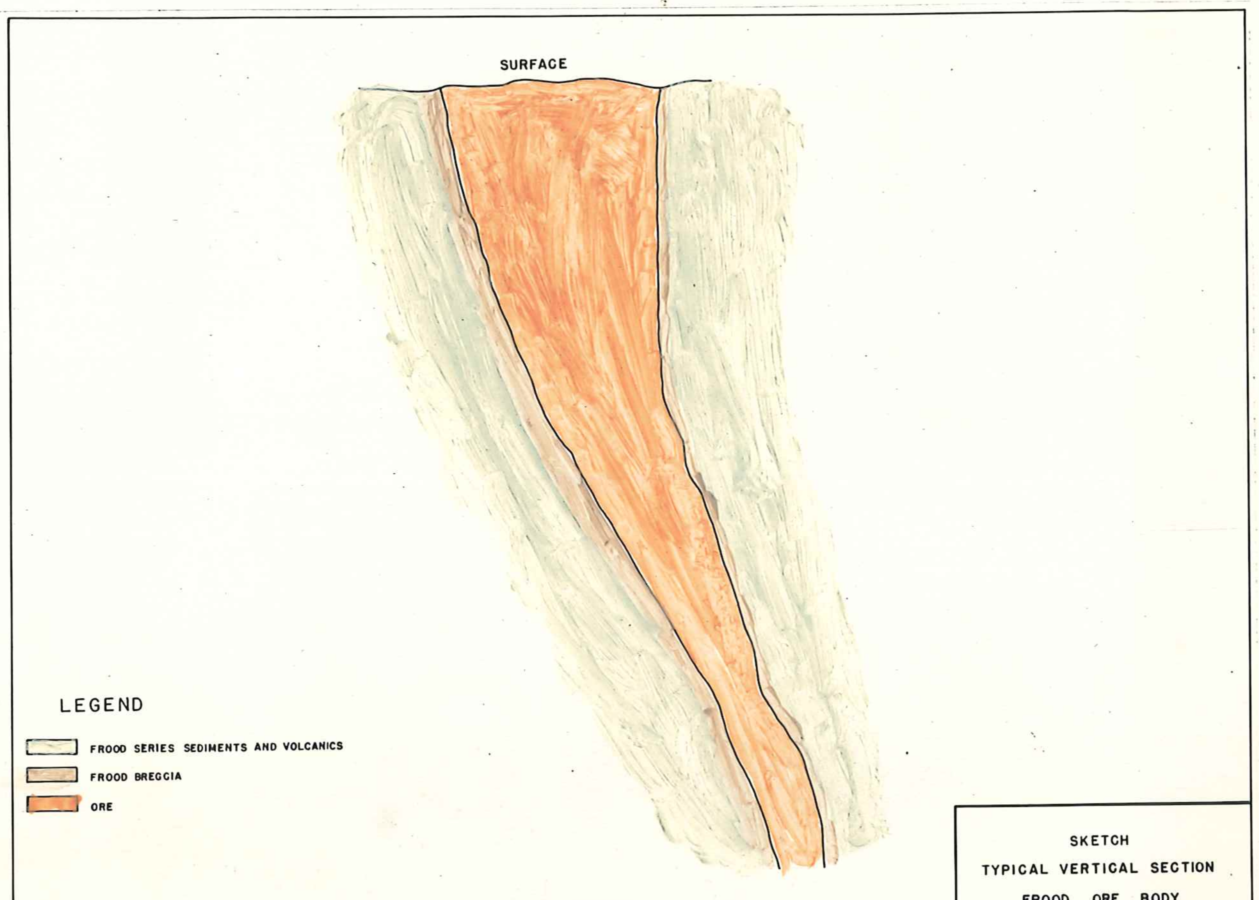


FIG.—62A.

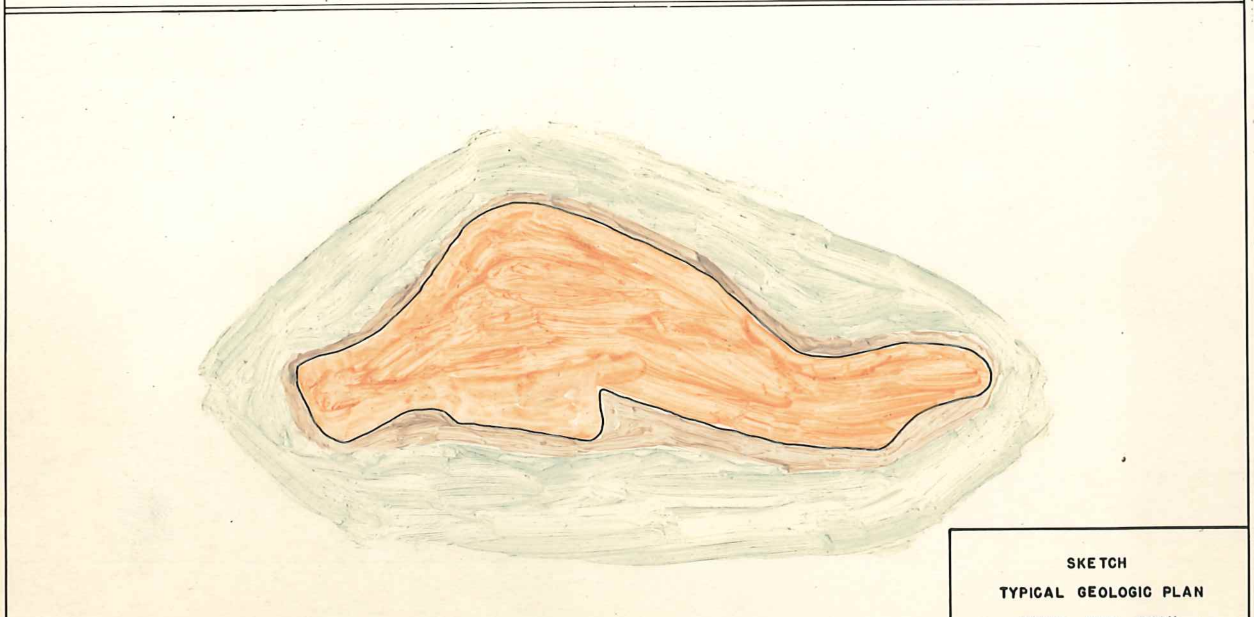


FIG.—62B.

carbonate, brecciated and partly replaced by sulphides, occur at the contact. The essential minerals in the massive ore are: chalcopyrite, cubanite, pyrrhotite, and pentlandite, and the accessory minerals are galena, and arsenides and sulpharsenides of cobalt and nickel. The ratio of copper to nickel averages about 5:1, and the ratio of pyrrhotite to pentlandite is variable but averages lower than that for the disseminated ore.

Murray Mine

The Murray mine is situated about three miles northwest of Sudbury. A part of the ore occurs in lenticular masses of breccia at the base of the norite. This breccia is composed of an abundance of fragments of altered gabbro, greenstone, gray norite, and feldspathic rocks embedded in a fine-grained matrix, which mineralogically resembles norite, except that the plagioclase is less calcic than labradorite. In most places the noritic matrix has been almost completely replaced by sulphides. The contact between this breccia ore and the hangingwall norite is definite and sharp; but, in some places along the footwall, the breccia ore merges with the high grade, massive sulphide ore that occurs in the underlying granite and greenstone.

The general strike of these orebodies is northeast-southwest, and the average dip is about 40 degrees northwest.

The essential minerals are pentlandite, pyrrhotite, and chalcopyrite. The ratio of pyrrhotite to pentlandite is 6.8:1, and the ratio of copper to nickel is 1:2.

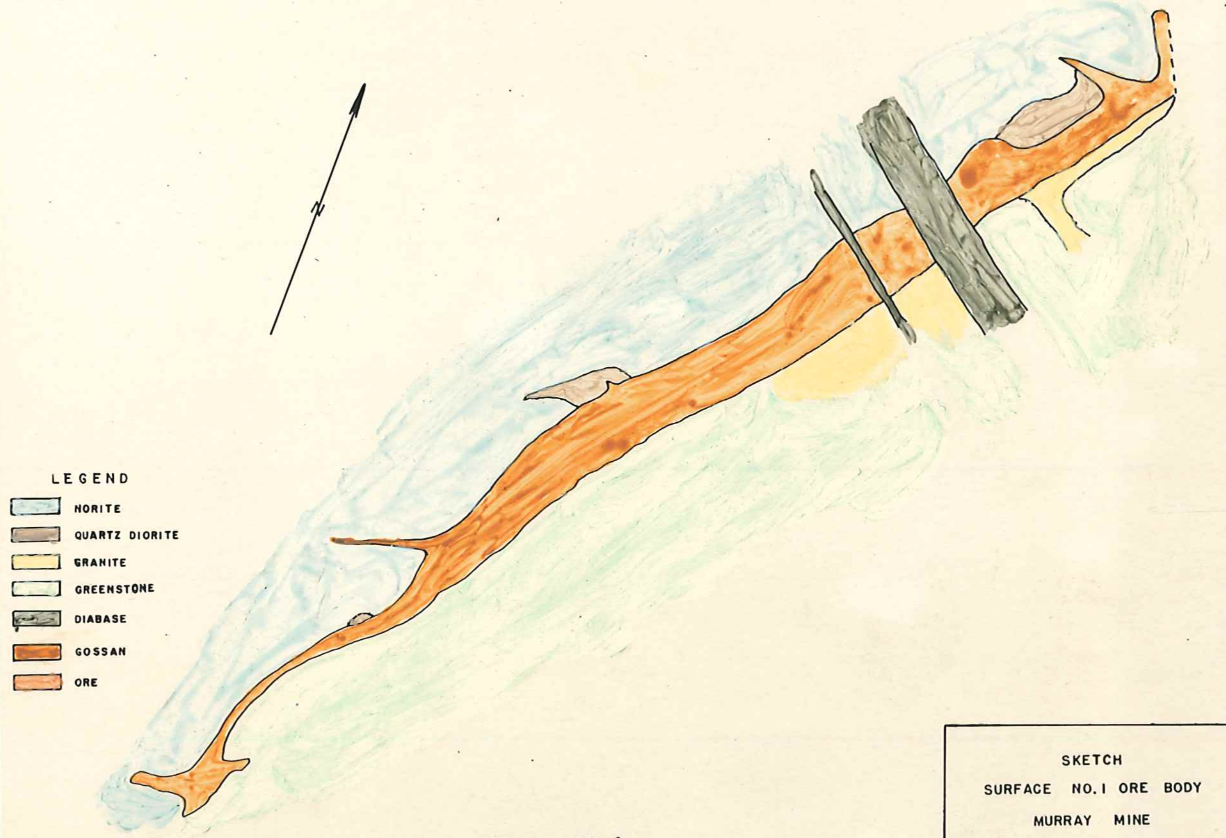


FIG.-63A.

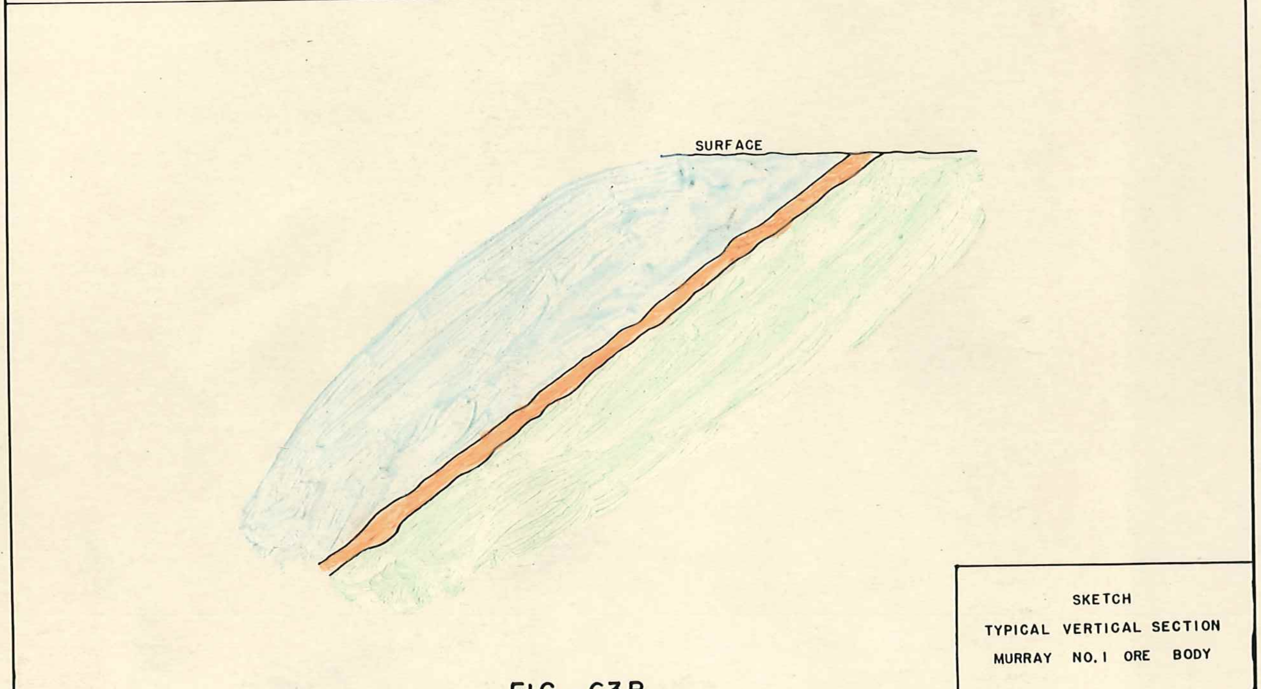


FIG.-63B.

Garson Mine

The Garson mine is situated in Garson township, about 10 miles northeast of Sudbury. It was operated for about 20 years by the Mond Nickel Company which, in 1929, was merged into the International Nickel Company of Canada. Oliver Hall, general superintendent of the former company, gave the following description of the orebodies that had been developed, under his direction, in this mine.

> Garson mine is a series of orebodies with a somewhat complex relation. The main ore zone has a northeast-southwest strike, and dips southeast at about 55 degrees, and the dip is still definitely in this direction at the deepest level, the 1400. This abnormal dip is apparently due to sharp folding in the norite-quartzite and norite-greenstone contact. This main zone has the shape of an arc approximately one-quarter of a circle. The dip is to the center of the circle; the hangingwall occupies the inside of the arc. Along this zone the ore is irregular in width, pinching out vertically and horizontally at intervals, and opening to widths of over 100 feet between pinches. Four other zones contain extensive ore areas: a northwest zone, orebody 16, an east-west zone with vertical walls at the southerly limit of the main zone, and a similar parallel zone at the northeast end of the main zone.
>
> Three bodies have been mined along a radial zone outside the main zone, called the northwest zone. Orebody 16 has been mined down to the 800 level and is a high-grade vein-like body outside the main zone, with a strike and dip similar thereto. The two vertical shear zones with east-west strikes and nearly vertical walls have been important sources of ore. In these the ore rakes east. The southerly zone contained only a short orebody near the surface, but the ore zone in this is over 700 feet long at the 800 and 1000 levels.
>
> Widths vary from pinches to over 100 feet. The northerly zone was first found to be important at the 800, and has a width of 20 to 100 feet and a length of

> over 600 feet up to the 600 level. ... At Carson the various bodies are irregular, and the unraveling of the ore zones at each level usually takes from two to three years.

At the time of the merger it appeared that this mine was approaching the depletion of its commercial ore, and there was a possibility that the operation would soon have to be considered as one of salvage. But the solution, by the geological staff, of the problem concerning the structural pattern that controlled the deposition of the ore, has resulted in the development of the largest ore reserves in the history of the mine.

Most of the ore has been developed, on the lower levels, along two shears having east-west strikes. These shears intersect a bay in the norite, resulting in structures that are somewhat similar to those found on the lower levels at Creighton mine. The dip of the northerly shear is 55 degrees south, and that of the southerly shear is 80 degrees south; the latter forms the fault contact between the norite and the older basement rocks. The flatter dip of the northerly shear results in its junction, at depth, with the southerly shear. Most of the ore that is found along these structures is massive and fine-grained and contains many visible rock fragments; some of the ore is coarser-grained and contains fewer rock fragments, and appears to owe its texture to the less-crushed host rock in which it is found.

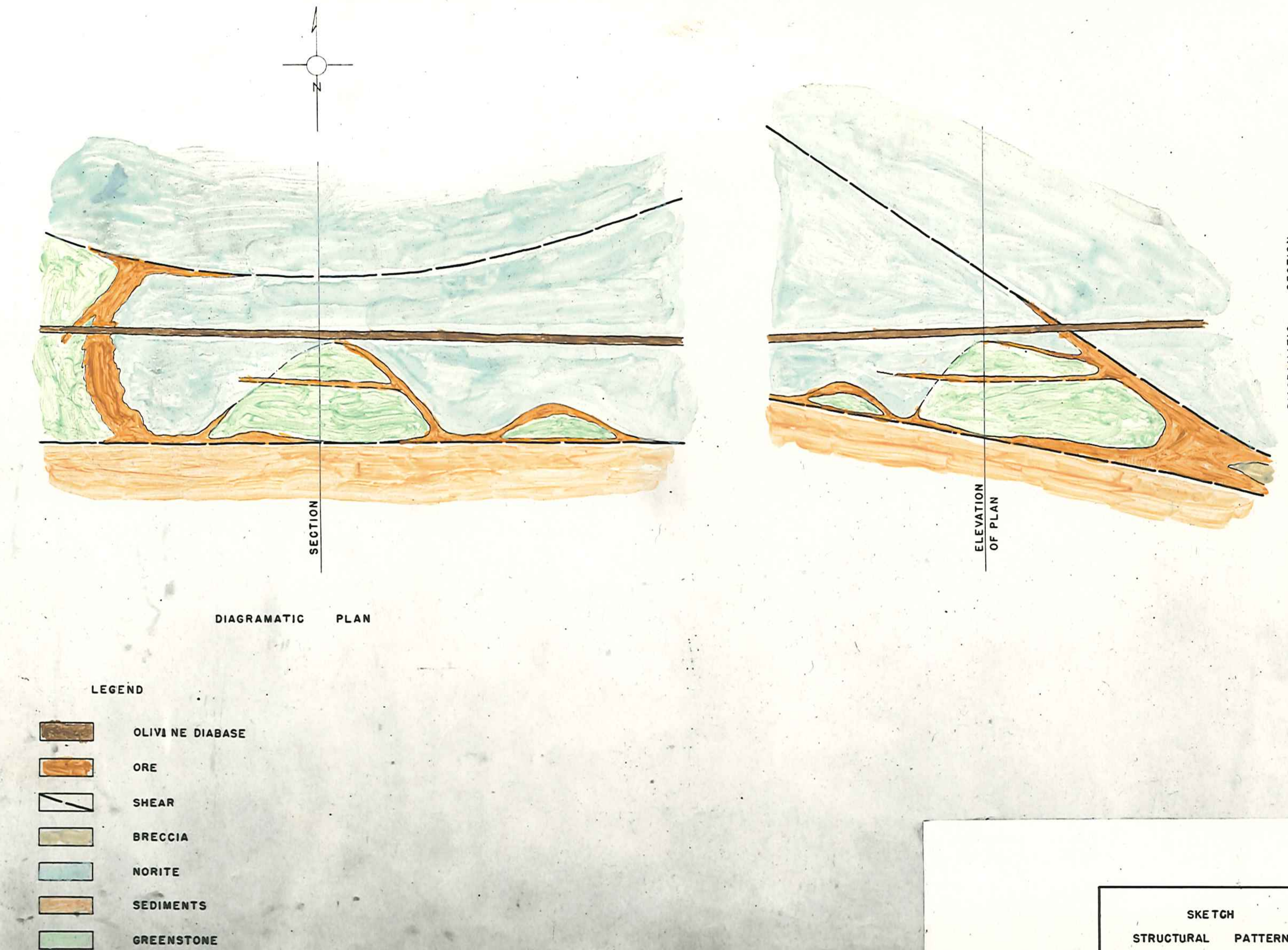


FIG.—64.

SKETCH
STRUCTURAL PATTERN
GARSON MINE

varies from a few degrees North to a few degrees South; in the latter case the norite forms the footwall of the orebody.

There are three general types of ore: breccia ore, massive sulphide ore, and disseminated ore. The breccia ore constitutes the bulk of the orebody and is composed of numerous rounded to subangular fragments, most of which are from the wallrocks, but some are of clear, glassy quartz, embedded in a matrix of fine-grained sulphides; this fine-grained texture appears to have been inherited from the original rock matrix. The massive sulphide ore is coarser-grained than the breccia ore, and is usually composed of pyrrhotite, pentlandite, chalcopyrite, and remnants of silicate minerals. The disseminated ore is found as replacement of both the norite and the older wall rocks.

Pyrrhotite, pentlandite, and chalcopyrite are the principal metallic minerals, with cobalt and nickel arsenides as accessory minerals. Minor amounts of galena and sphalerite, of no commercial value, occur with the other sulphides. The ratio of pyrrhotite to pentlandite is about 5:1, and the ratio of nickel to copper is about 2:1

Levack Mine

The Levack mine is situated about four miles northeast of Levack Station, which is on the main line of the Canadian Pacific Railway, 20 miles northwest of Sudbury. It is the most

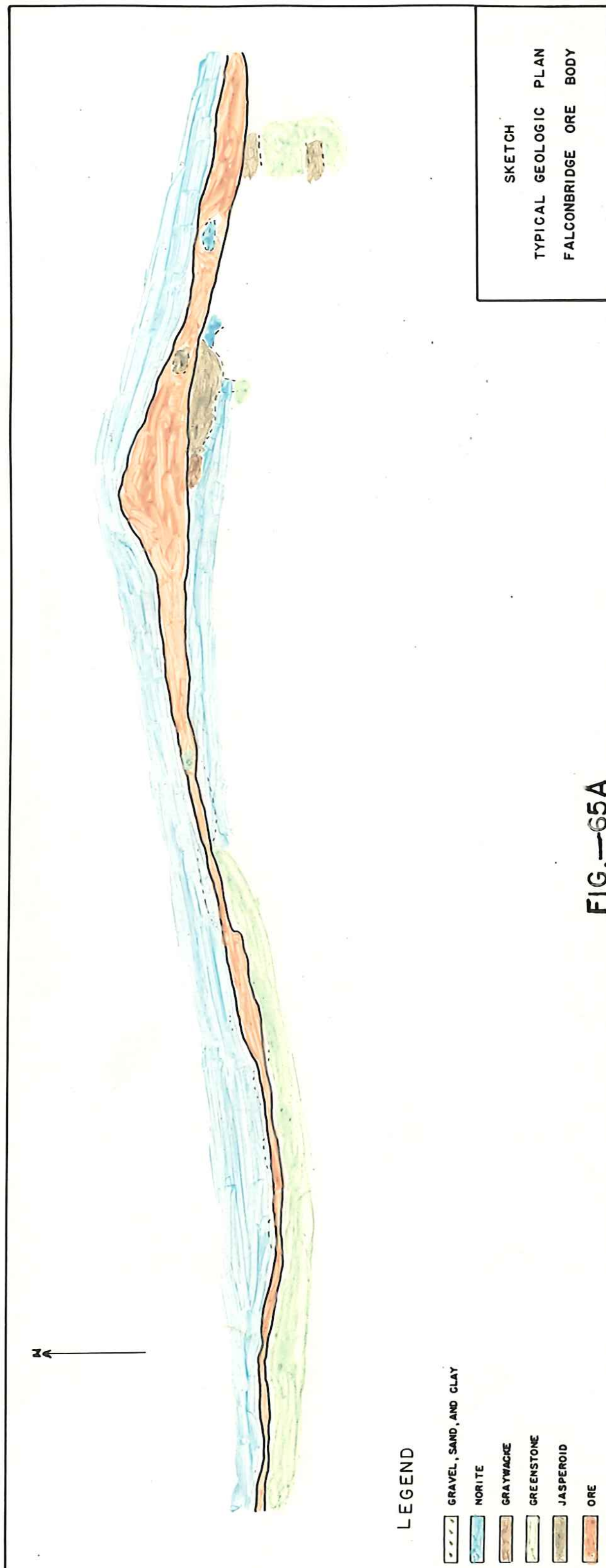
Hall's description of the main ore zone having ". . . the shape of an arc approximately one-quarter of a circle" etc. applies to the zone in the west side of the norite bay between the two east-west shears. This zone is composed of a heavily mineralized breccia, similar to that found at the base of the norite in the Murray mine.

The essential minerals are pyrrhotite, pentlandite, and chalcopyrite with lesser amounts of gersdorffite and violarite. The ratio of pyrrhotite to pentlandite is 4.7:1, and that of copper to nickel is about 1:1.

Falconbridge Mine

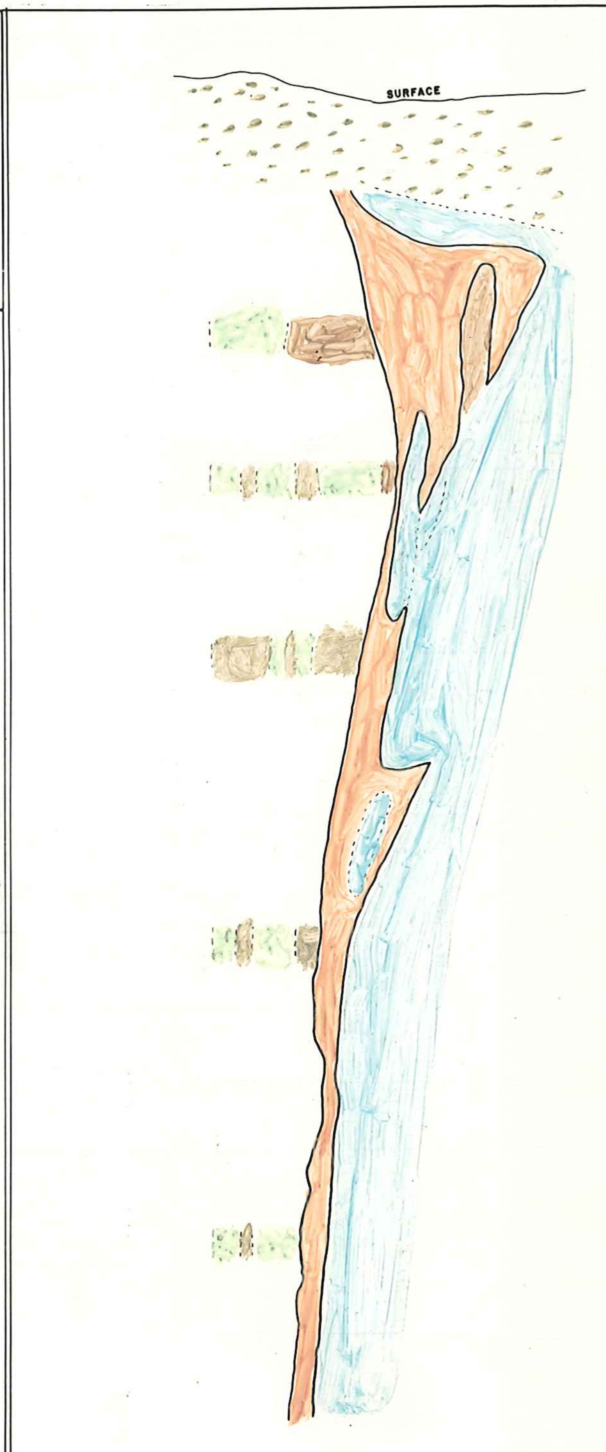
The Falconbridge mine, owned and operated by the Falconbridge Nickel Mines, Limited, is situated in Falconbridge township about 13 miles norhheast of Sudbury. The ore deposit occurs along a fault zone that generally follows the contact of the norite and the older pre-Huronian sediments and volcanics; but both the norite and the older rocks have been involved in the faulting, resulting in segments or slabs of each type being found on the opposite sides of the fault on which the main bodies of these rocks occur.

The main orebody pinches and swells, both vertically and horizontally, resulting in widths that vary from a few feet to more than 50 feet, and has a total length of about 9,000 feet. It has a strike of about N. 80 degrees E. and a dip that



SKETCH
TYPICAL GEOLOGIC PLAN
FALCONBRIDGE ORE BODY

FIG.—65A



SKETCH
TYPICAL GEOLOGIC SECTION
FALCONBRIDGE ORE BODY

FIG.—65B.

to those of the host rocks in which they occur. As early as 1905, Coleman (14, p. 52) noted this fact; in describing the texture of the ore on the dump at Murray mine he states that ". . . as at most other nickel mines in the district, the ore being in coarse grains when the rock is coarse-grained, and vice-versa."

Description of the Various Mines in the Sudbury Area

Creighton Mine

The Creighton mine is situated about 11 miles west of Sudbury. The ore deposits lie in a distinct embayment in the footwall rocks; in addition to norite, this embayment is partly filled with an irregular mass of breccia, somewhat similar to the quartz diorite "offset" rock, even to the extent of having a thin massive marginal phase containing no fragments of older rocks. The contact of this breccia with the norite is not always sharp; there is often an actual gradation, over a few inches, from the breccia containing sulphides to coarse norite free from sulphides. Large and small fragments of normal gray norite are found within the breccia.

In addition to granite, the principal footwall rock found in this area, various other types such as quartzite, arkose, gabbro, and greenstone are in contact with the norite important ore deposit found on the North range, and was first developed by the Mond Nickel Company, Limited, and was operated by this company until its merger with the International Nickel Company of Canada, in 1929.

Three principal orebodies, separated by several thousand feet along the strike, have been developed at this mine. Most of the ore occurs near the footwall of a zone of granite breccia that characterizes the norite-gneiss contact in this area and extends into the fractured footwall gneiss for distances that range from a few feet to a maximum of about 850 feet; it rarely extends to the hangingwall norite.

The granite breccia is composed of numerous angular to sub-angular fragments of gneiss, altered gabbro, and peridotite, and fine-grained diorite in a completely recrystallized granitic matrix. The greater part of this zone of breccia is barren or only slightly mineralized, but in some places sulphides occur as irregular veinlets, patches, and disseminated spots and grains, in sufficient amounts, throughout the matrix to constitute orebodies; this type of ore merges with stringers and lenses of sulphides in the fractured footwall gneiss. The footwall gneiss is unquestionably a product of granitization of sediments and igneous rocks; in many places the primary structures, such as bedding of the sediments and flow structures of the volcanics are clearly preserved. It is evident that the granite breccia is later than the norite, since the norite adjacent to the contact is altered to a coarse-grained aggregate of epidote-zoisite, chlorite, and amphibole. In some places the granite breccia intrudes the main norite mass for distances up to several hundred feet.

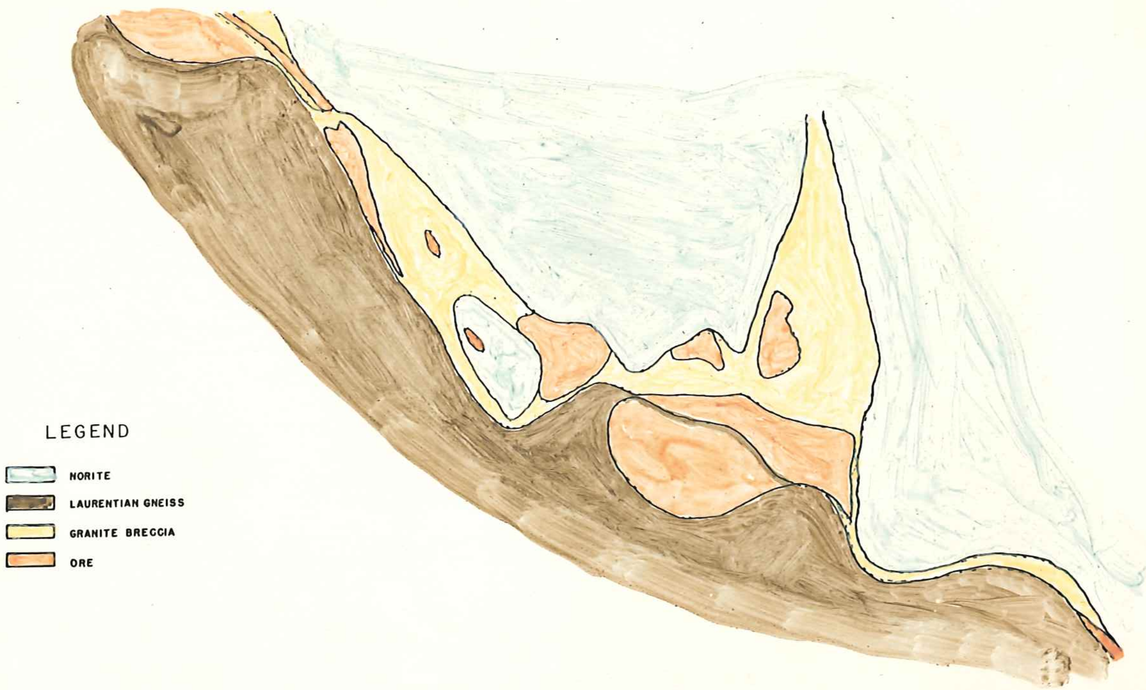
The ore occurs as three distinct types: (1) approximately 65 per cent of the production has been disseminated ore that occurs as replacement of the matrix of the granite breccia; (2) approximately 30 per cent has been massive sulphide ore that occurs as stringers and masses in the granite breccia and in the fractured footwall gneiss; (3) approximately 5 per cent has been disseminated ore in altered norite. The disseminated sulphides corrode, vein, and embay the silicate minerals in the altered norite and those in the matrix of the granite breccia; but the larger fragments are practically barren of sulphides; the same is true of the rocks that are adjacent to stringers, veins, or bodies of massive sulphides.

The orebodies usually parallel the contact of the norite and granite breccia, and have an average dip of 40 degrees South; their form is controlled by brecciation and this has resulted in thick, irregular-shaped lenses which sometimes change abruptly, either vertically or horizontally, from comparatively narrow widths to several hundred feet.

The principal minerals are pyrrhotite, chalcopyrite, and pentlandite, with lesser amounts of pyrite and magnetite. The ratio of pyrrhotite to pentlandite is about 5:1, and the ratio of copper to nickel is about 1:2.

FIG.—66A.

SKETCH PLAN
NO. 7 LEVEL LEVACK ORE BODY

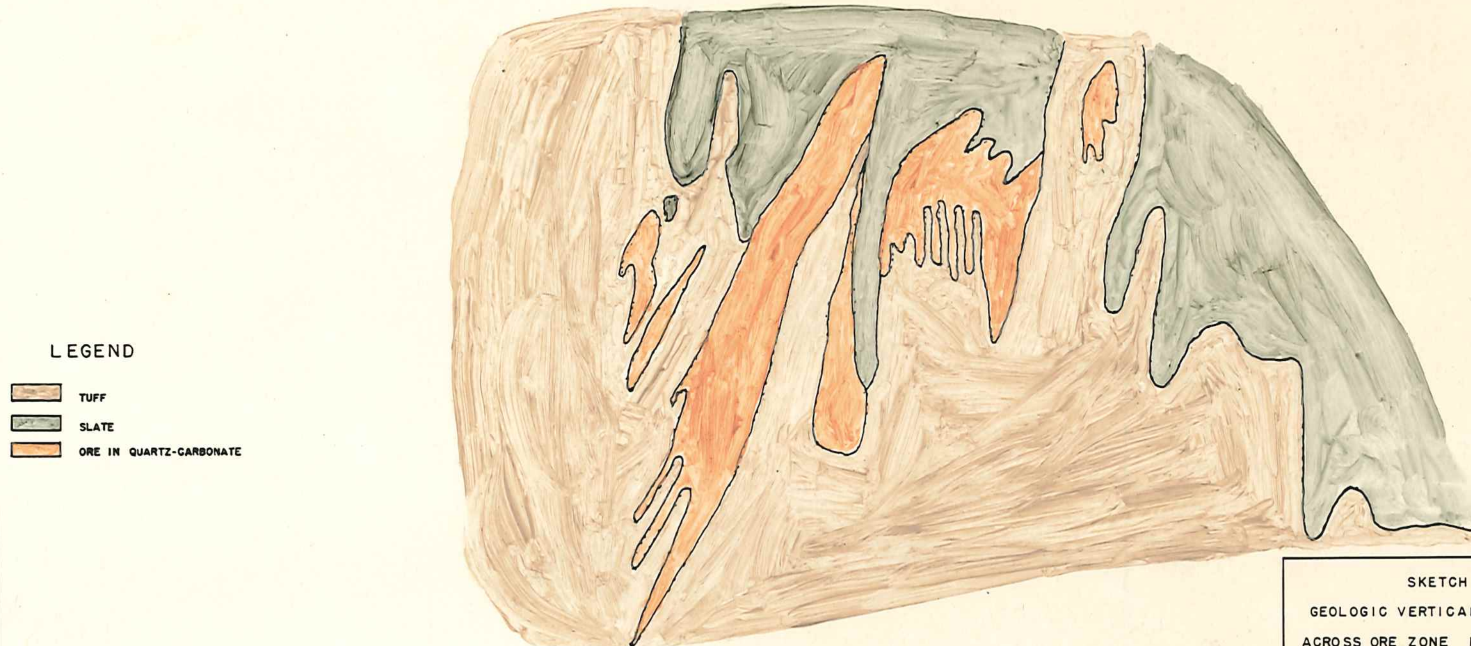


SKETCH
LEVACK MINE SECTION
SHOWING RELATIONSHIP
BETWEEN GRANITE BRECCIA
AND
THE SUDBURY INTRUSIVE

FIG.—66B.

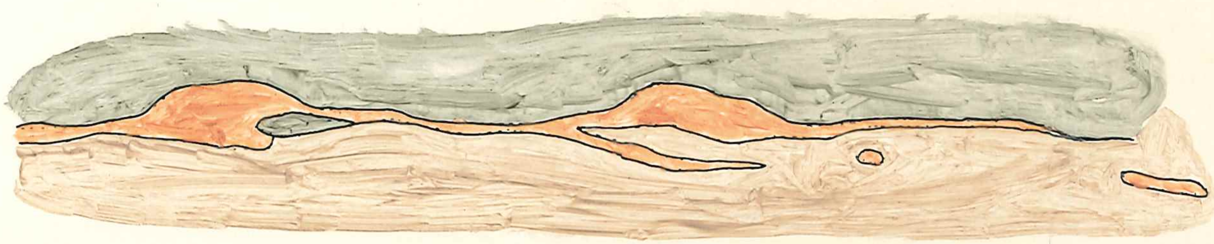
Errington Mines

This property is situated about 17 miles, by highway, northwest of Sudbury. The strong fault system that offsets the rim of Sudbury basin at its southwestern end passes into smaller faults and broad shear zones in the slate and tuff of the inner basin. The most important of these zones occurs near the southwestern contact of the slate and fine-grained tuff. A series of quartz carbonate lenses, which have replaced sections of the fine-grained tuff along flanks and crests of folds, have been found along this zone for a distance of more than six miles. More or less of this quartz carbonate has been replaced by complex ore consisting of pyrite, sphalerite, chalcopyrite, and galena with minor amounts of pyrrhotite and pentlandite. These sulphide deposits range in size from small lenses that contain a few thousand tons to one that contains more than two million tons. Several million tons of material with an average grade of 20 per cent pyrite, 5 per cent zinc, 1 per cent copper, 1 per cent lead, 2 ounces silver, and 0.03 ounces gold were developed in these mines, but the operations were discontinued when the price of base metals dropped to figures which made the treatment of this grade unprofitable. Tentative plans for the reopening of these mines are now being made by the Ontario Pyrites Company, Limited.



SKETCH
GEOLOGIC VERTICAL SECTION
ACROSS ORE ZONE NO. 2 SHAFT
ERRINGTON MINE

FIG.—67A.



SKETCH
GEOLOGIC PLAN ALONG ORE ZONE
500-FT. LEVEL NO. 1 SHAFT
ERRINGTON MINE

FIG.—67B.

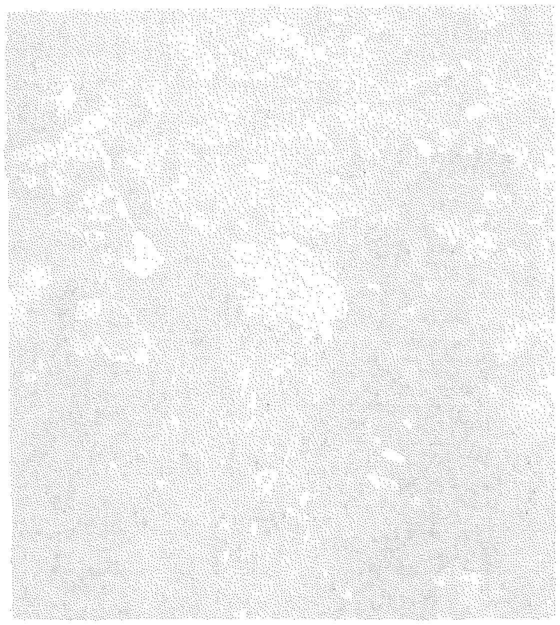


Fig. 68

Hornblende and biotite partly replaced by pyrrhotite, chalcopyrite and pentlandite. Lee. 4000 ft. level Garson mine. [illegible]

Fig. 69

Plagioclase, quartz, hornblende, and muscovite partly replaced by pyrrhotite, chalcopyrite, and pentlandite. Lee. [illegible]

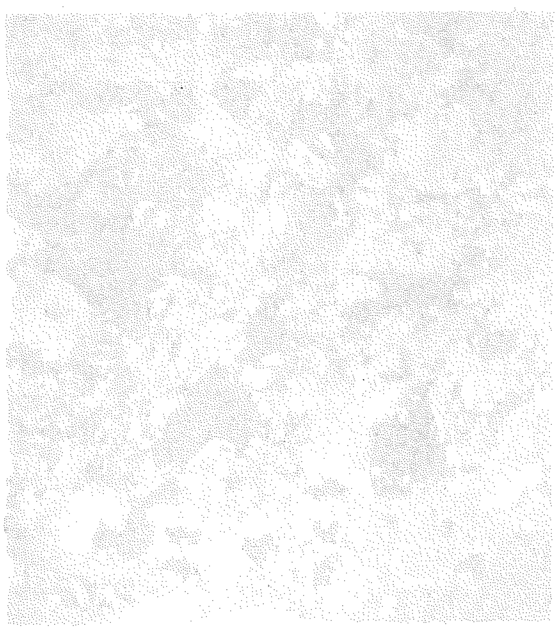


Fig. 70

Secondary amphibole, clinozoisite, epidote, quartz, and plagioclase partly replaced by pyrrhotite, pentlandite and chalcopyrite. Lee. 3500 ft. level Falconbridge [illegible]

Fig. 71

Fragments of [illegible] replaced by pyrrhotite, chalcopyrite, and pentlandite. Lee. 750 ft. level Falconbridge [illegible]

Fig. 72
Plagioclase, pyroxene, and biotite partly replaced by pyrrhotite, chalcopyrite, and pentlandite. Loc. Creighton mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 424

Fig. 73
Plagioclase, secondary amphibole, and epidote partly replaced by pyrrhotite, chalcopyrite, and pentlandite. Loc. Murray mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 450

Fig. 74
Plagioclase, secondary amphibole, and epidote partly replaced by pyrrhotite, chalcopyrite, and pentlandite. Loc. Murray mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 450

Fig. 75
Plagioclase, Pigeonite, enstatite, and biotite partly replaced by pyrrhotite, chalcopyrite, and pentlandite. Loc. Murray mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 377

Fig. 76
Hornblende, plagioclase, quartz, and chlorite partly replaced by pyrrhotite, chalcopyrite, and pentlandite, Loc. Frood open-pit. X $20\frac{1}{2}$, plain pol. light.
Sec. No. 42

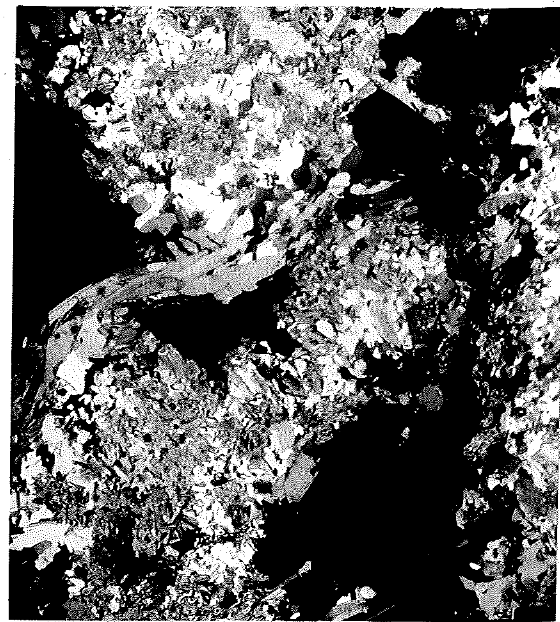


Fig. 77
Biotite, hornblende, plagioclase, and quartz partly replaced by pyrrhotite, chalcopyrite, and pentlandite. Loc. 1800 ft. level Frood mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 347

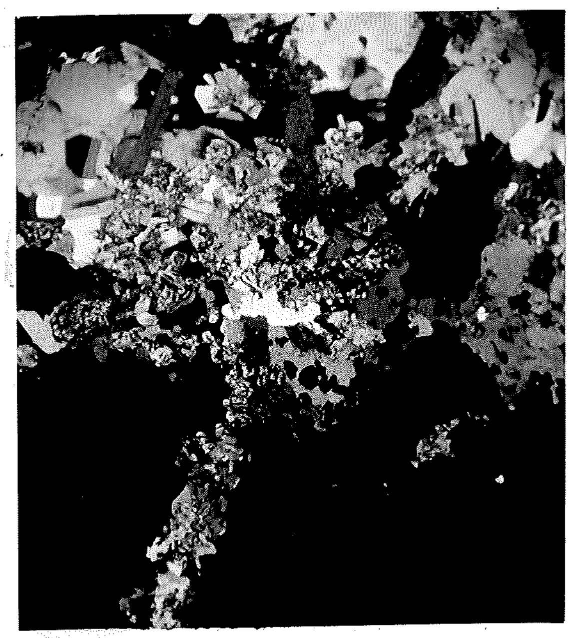


Fig. 78
Biotite, hornblende, plagioclase, and quartz partly replaced by chalcopyrite, pyrrhotite, and pentlandite. Loc. 2800 ft. level Frood mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 344

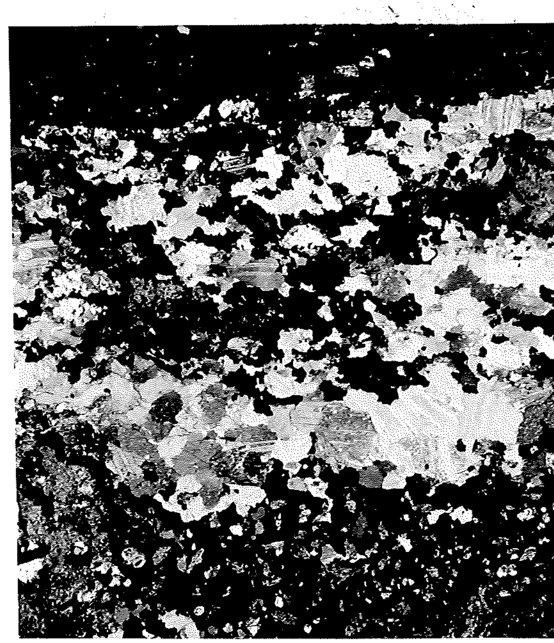


Fig. 79
Secondary amphibole, biotite, quartz, and carbonate partly replaced by pyrrhotite, chalcopyrite, and pentlandite. Loc. H.W. 1600 ft. level Garson mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 263

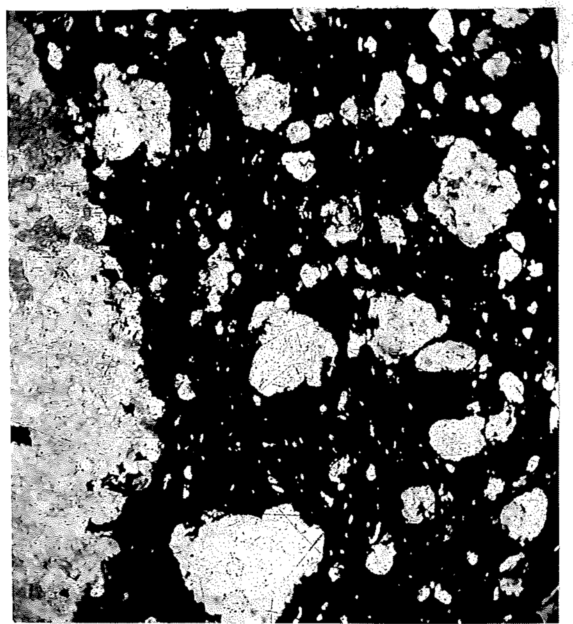


Fig. 80
Fragments of quartz, chlorite, feldspar, carbonate, and epidote partly replaced by pyrrhotite, pentlandite, and chalcopyrite. Loc. 1000 ft. level Falconbridge mine. X $20\frac{1}{2}$, plain pol. light.
Sec. No. 5

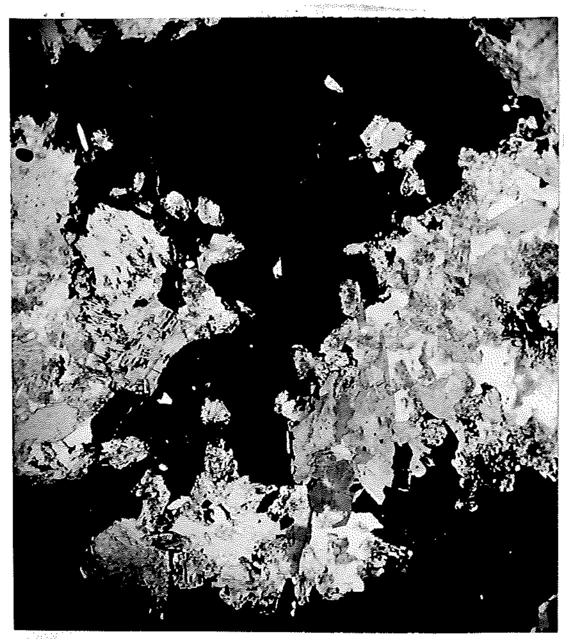


Fig. 81
Secondary amphibole, biotite, plagioclase, and quartz partly replaced by pyrrhotite, chalcopyrite, and pentlandite. Loc. 1400 ft. level, Levack mine. X $20\frac{1}{2}$, plain pol. light.
Sec. No. 297

Fig. 82
Secondary amphibole, plagioclase biotite, and quartz partly replaced by pyrrhotite, chalcopyrite, and pentlandite . Loc. Drill-core, Whistle mine. X $20\frac{1}{2}$, plain pol. light.
Sec. No. 300

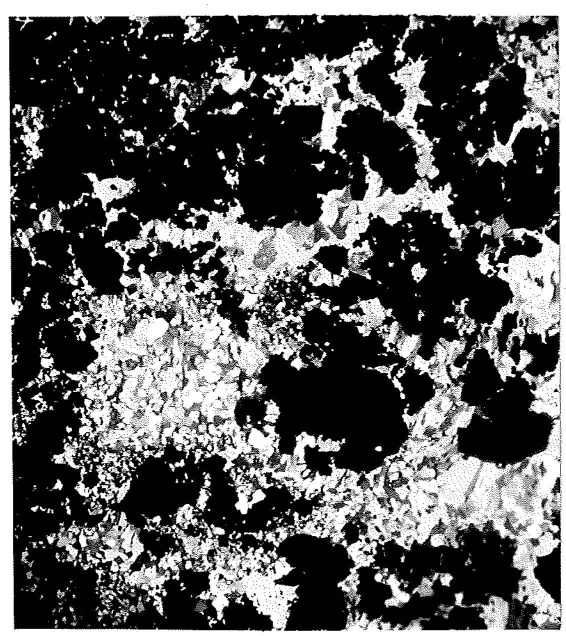


Fig. 83
Quartz and carbonate replaced by pyrite, and pyrite partly replaced by chalcopyrite. Loc. 500 ft. level Errington mine. X $20\frac{1}{2}$, X-nicols.
Sec. No. 44

Summary As to the Mode of Origin of the Sudbury Nickel-Copper Ores

The observations of early workers in this area that most of the commercial orebodies occurred near the outer margin of the norite resulted in the theory, first suggested by Bell (4), that the orebodies were genetically closely related to the norite. Walker, Barlow, Coleman, and Moore (48, 2, 14, 11, 15) accepted Bell's suggestion, and so convincingly developed the theory of magmatic segregation, in situ, for these ores, that, for many years, most geologists and authors of text books dealing with the genesis of metallic ores, cited these deposits as classic examples of the above process.

C. W. Dickson (25) was the first worker in this area to seriously dispute the above theory. He spent the field seasons of 1901 and 1902 in the study of conditions at the mines that were in production or under development at that time. The remainder of the above two-year period was devoted to microscopical and petrographical studies of the material which he had collected in the field. In his conclusion he states:

> It might be safely stated that at present the whole weight of evidence points to the formation of the Sudbury ore-bodies as replacements along crushed and faulted zones, with only minor indications of open cavities.

> Previous observers have naturally been impressed by the massive character of the sulphides, in which are found the minerals of the enclosing rock, and this seems to fall in readily with the idea of an igneous origin.
>
> The clue to the interpretation of the matter, however, appears to be furnished by the leaner material, where the relations have not been obscured or obliterated by the excessive development of sulphides.

The published results of Dickson's careful and systematic work were overshadowed, for many years, by the voluminous published statements of contemporary and later workers, who favored the theory of magmatic segregation, in situ, and it is only in recent years that several workers in this area, including the writer, recognize that the norite had solidified before the formation of the structural features that have controlled the localization of the ore deposits.

APPENDIX

CATALOGUE OF METALLIC MINERALS FOUND IN THE SUDBURY ORES (38)

MAGNETIC PYRRHOTITE ($FeS_{1.157}$), the most abundant sulphide in the Sudbury area, contains from .40 to .50 per cent nickel, either in chemical combination with it or as finely divided pentlandite.

NON-MAGNETIC PYRRHOTITE ($FeS_{1.10}$) occurs in the same manner and with the same mineral association as the magnetic variety; but, in the hand specimen, it has a more brilliant luster and a deeper red color.

PENTLANDITE occurs as thin blades and veinlets in pyrrhotite, as "eyes" or crystals in massive sulphide, and as coarsely crystalline masses.

SILVER-BEARING PENTLANDITE, a new mineral, which Michener described as having a "fox-red" color, has only been found in the ore from the lower levels of the Frood mine. It occurs as small grains less than one millimeter in diameter, associated with galena and as oriented intergrowths with normal pentlandite.

COBALT PENTLANDITE was first found in the Garson mine, occurring as nodules along a shear zone. It was first examined and isolated by G. A. Harcourt who described it as a mineral that in polished section shows a rough, yellow surface, is harder than normal pentlandite, is weakly magnetic, and is isotropic.

MAUCHERITE and NICCOLITE occur as veins and bands around the contacts of some of the orebodies, as replacement remnants in sulphide ore, and as stringers replacing quartz and carbonate. Michener calculated the formula for maucherite, from chemical analysis, as $Ni_{11}As_8$.

GERSDORFFITE in the Sudbury ores is a combination of CoAsS and NiAsS with a considerable amount of iron.

NiBiS, one of the new minerals discovered by Michener and described as having the following properties: color, dark bronze on fresh cleavages. Luster metallic. Streak black. Fracture uneven. Hardness 3; specific gravity 7.5 (estimated from its behavior on the superpanner). It is found in the ores in the Frood mine that contain galena.

CHALCOPYRITE is found as massive sulphide, as stringers, as replacement of the arsenical ores, and as a part of the disseminated ores. Over 85 per cent of the copper produced in this district occurs as chalcopyrite.

CUBANITE is closely associated with pyrrhotite and chalcopyrite, and is often found as a lamellar intergrowth with the latter mineral. Almost 15 per cent of the copper produced in this area occurs as cubanite.

BORNITE and TETRAHEDRITE have been reported from two localities, but they are of rare occurrence.

SPERRYLITE is found in small quantities in practically all the copper-nickel ores of the district. It occurs as rounded crystals in various forms of the cubic system, sometimes having inclusions of gold and other rare and precious metallic minerals.

$PdBi_3$ and Pd_3Bi_3, two new minerals discovered by Michener, occur with precious metals and minerals associated with the nickel arsenides in the Frood mine. $PdBi_3$ is described as having the following properties: color gray; streak black; brittle, hardness 2.5; luster metallic, splendant on fresh cleavage but tarnishes readily; cleavage (001) perfect, (100) less perfect; specific gravity 12.5 (Harcourt). Pd_3Bi_3 is described as follows: color gray; streak black; fracture uneven; brittle; hardness 2.5; luster dull metallic; cleavage, none seen.

RHODIUM, IRIDIUM, and RUTHENIUM have been identified spectrographically as constituents of other minerals. Sperrylite sometimes contains iridium in addition to rhodium and palladium. Iridium and ruthenium have been detected in tetradymite concentrate, and iridium and rhodium in the concentrate of the palladium minerals. Dark-colored gold showed the presence of palladium and iridium.

ELECTRUM is found most abundantly in small fractures in the contact rocks, as platings on secondary hornblendes, as inclusions in the platinum group minerals, and in the arsenide type of mineralization. Its composition varies from approximately equal parts of gold and silver to nearly pure gold.

HESSITE is associated with galena, sphalerite, and chalcopyrite, and is found with other precious metals in the contact rocks. Most of the silver produced in this area comes from this mineral.

SELENIUM is produced, in copper refining, in much greater quantity than tellurium, but no selenium compound has yet been recognized in the ore.

TETRADYMITE has been found as small grains in non-magnetic pyrrhotite, as intergrowths with native bismuth in the galena and NiBiS type of mineralization, and as small grains in galena.

METALLIC BISMUTH is found in the NiBiS-galena type of mineralization. The color varies from creamy white to bronzy pink. Spectrographic analyses showed that some was fairly pure, some contained a small amount of silver, and some contained both silver and lead. In the process of preparing some of this material for polished sections, some of it melted, in a bakelite press, at a temperature below that of the melting point of the pure metal. This lead Michener to believe that some of the bismuth is alloyed with small amounts of lead and silver.

BISMUTHINITE is found in the same mineral associations as native bismuth, it is usually found as small grains in galena from which it is distinguished by its strong anisotropism.

GALENA, in the Frood mine, occurs as a minor constituent throughout the massive sulphide, and more abundantly in the sulphide areas at the ends of the orebody and in the lower part of the flat-bottomed sulphide masses. It is also found associated with sphalerite, marcasite, and calcite in veinlets filling fractures in the earlier sulphides.

MAGNETITE is usually found as rounded octahedra in all the sulphide ores. In some Creighton ores high in pyrrhotite it forms up to 20 per cent of the total volume. The larger crystals are partly replaced by sulphides.

ILMENITE is much less common than magnetite, but at the contacts it is sometimes found as blades up to one millimeter in width and several centimeters in length, and as remnants due to sulphide replacement.

STANNITE was found as small grains in the galena-bismuth type of mineralization.

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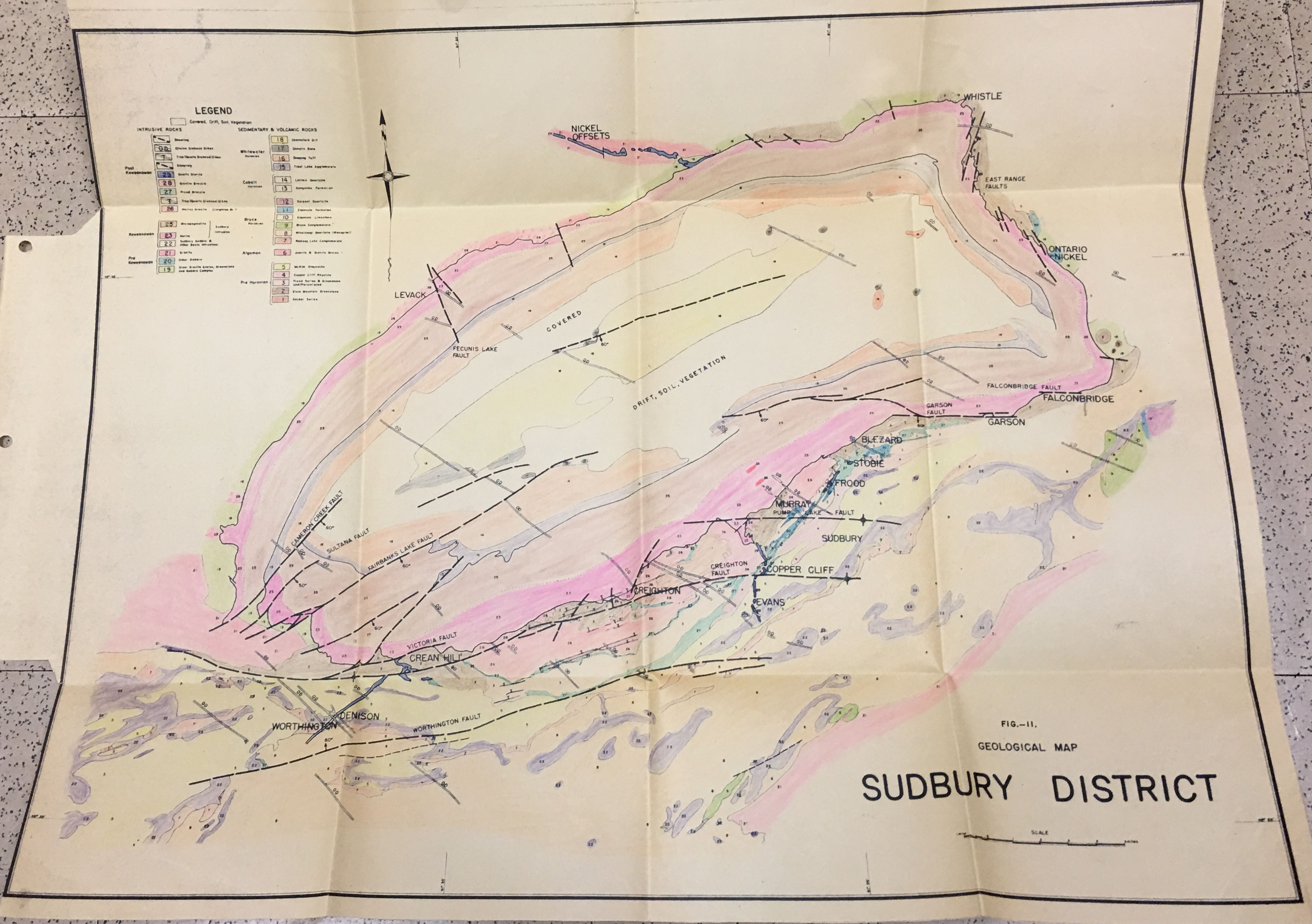

FIG.-11.

GEOLOGICAL MAP

SUDBURY DISTRICT