Theses and Dissertations (Comprehensive)

1970

A Comparative Study of Nickel Sulphide Deposits Within the Area of the Canadian Shield

Robert G. Kreiner
Wilfrid Laurier University

A COMPARATIVE STUDY OF NICKEL SULPHIDE DEPOSITS

WITHIN THE

AREA OF THE CANADIAN SHIELD

BY

Robert G. Kreiner

Submitted in partial fulfillment of the

requirements for the M.A. Degree in Geography

Faculty of Graduate Studies

Waterloo Lutheran University

Waterloo, Ontario

1970

ACKNOWLEDGEMENTS

ABSTRACT

In order to plan the future development of the Canadian
Shield within a conceptual framework as suggested by the Mid-
Canada Corridor concept, both the presently developed and pot-
ential, natural resources of this area need to be evaluated for
knowledgeable development and management. To this purpose,
various areas of nickel sulphide deposits within the area of
the Canadian Shield have been studied with the object of deter-
mining similar sequences of intrusive events and their spatial
relationships.

Within the Sudbury area, Ontario, five periods of intrusive
activity have been recognized, each period characterized by an in-
itial intrusion of acidic composition, followed in turn by one or
more intrusions of basic composition. Genetic relationships among
these various intrusives have been noted by the presence of micro-
graphic intergrowths of quartz and feldspar. Increasingly, signi-
ficant concentrations of nickel sulphides are indicated as having
been emplaced at the terminations of the three latest periods.
Such features are suggested as being indicative of a process of
nickel sulphide concentration and emplacement, namely magmatic
differentiation at depth as initially hypothesized by E. Howe
(1914) and later modified by A.M. Bateman (1917). A third con-
cept of the Sudbury irruptive is suggested as having consisted
of an initial emplacement of micropegmatite, closely followed
by a differentiated fraction of norite. The structural shape
of the irruptive at depth is suggested by a diagrammatic cross

section, suggestive of the descriptive hypothesis of C.W. Knight (1917).

Sequences of acidic to basic, intrusive events are also indicated in the areas of Lynn Lake, Manitoba, Moak Lake-Setting Lake, Manitoba, Bird River, Manitoba, Werner Lake-Gordon Lake, Ontario, Shebandowan, Ontario and Marbridge, Malartic, Quebec. The evidence reviewed indicates spatial relationships of nickel sulphide mineralization not only with basic intrusives but also with acidic intrusives and zones of tension fractures.

TABLE OF CONTENTS

Table of Contents (continued)

Table of Contents (continued)

LIST OF TABLES

LIST OF ILLUSTRATIONS

List of Illustrations (continued)

CHAPTER I

SCOPE OF THE STUDY

Introduction

In terms of area, the Canadian Shield represents approxi-
mately half of the total land area of Canada, its largest physio-
graphic region, and also its least developed region. If the future
development of this vast and somewhat inhospitable terrain is to be
planned within a broad, conceptual framework, as suggested by the
Mid-Canada Development Corridor concept, both the presently devel-
oped and potential resources of this area need to be fully evalua-
ted for knowledgable development and management. It would appear
significant that Sudbury, the area's second largest city, is vir-
tually dependent on a continuing development of nickel ore deposits
for its continued existence. After 84 years of production in the
Sudbury area and more than 75 studies, little agreement has been
reached as to either the mode of concentration or the emplacement
of the nickel deposits. In 1948, A.B. Yates, a former chief
geologist of the International Nickel Company of Canada Limited,
considered the Sudbury deposits to be "unique in their occurrence,
structure and genesis". [1]

Purpose of Study

The writer does not consider the Sudbury deposits or any
of the presently developed nickel ore deposits within the area of
the Canadian Shield to be of an unique nature. It is his

1

contention that all of these deposits should share some similarities of occurrence, structure and genesis which might prove indicative of a common process of nickel sulphide concentration and emplacement. An understanding of such a process of formation could lead to the full development of the existing resource-areas within the Canadian Shield, and also to a more knowledgeable assessment of potential resource-areas considered necessary for any proposed concept of planned development.

The object of the study has been a compilation of evidence indicative of similar sequences of events and their spatial relationships at each of the following nickel resource-areas. (Figure 3, page 6).

> Sudbury area, Ontario
>
> Lynn Lake area, Manitoba
>
> Moak Lake-Setting Lake area, Manitoba
>
> Bird River area, Manitoba
>
> Werner Lake-Gordon Lake area, Ontario
>
> Shebandowan area, Ontario
>
> Marbridge area, Malartic, Quebec

An in-depth-study has been made of the Sudbury area due to three considerations, namely the voluminous amount of published evidence available, the many theories of structure and genesis presented, and the potential of assembling a complete sequence of events as a potential model for comparison with the other nickel resource-areas.

Evidence presented in this study has been gathered from numerous published and unpublished sources. Personal observation of various petrological and structural features has been limited to the Hardy and Strathcona mines of the Sudbury area and to the Birchtree mine of the Moak Lake-Setting Lake area. Similarity of features in these two areas has encouraged the writer to pursue this comparative study.

Hypotheses of Nickel Sulphide

Concentration and Emplacement

Throughout the world, samples of igneous rocks have been found to contain increasingly higher percentages of nickel with increasingly greater contents of iron-magnesium and also lower contents of silicon-aluminum, as indicated by Table 1. The

Table 1

PERCENTAGE COMPOSITION OF INTRUSIVE ROCK TYPES

Rock Type	Classification of Rock Types	Nickel in%	Iron Oxides & Magnesia in%	Silica & Alumina in%
Granite	acidic	0.0002	4.4	78.7
Diorite	intermediate	0.004	11.7	73.4
Gabbro	basic	0.016	16.6	66.1
Peridotite	ultrabasic	0.20	43.3	45.9

Source: modified from The Winning of Nickel, 1967, p. 4.

basic problem exists that rock containing less than 0.5 per cent nickel cannot be economically mined and processed under present conditions. Consequently, nickel mineralization, found to be disseminated in basic and ultrabasic rocks in percentages of 0.016 and 0.20, has had to be concentrated by some naturally occurring process to percentages of 0.5 to 2.0 per cent for such deposits to have been economically minable. To explain such concentrations, three hypotheses of possible nickel sulphide concentration have been advanced for the Sudbury area over the past eighty years.

These hypotheses are summarized as follows.

(a) magmatic differentiation in place - concentration by a gravitational settling out of nickel sulphides from a cooling and crystallizing basic magma following its in-trusion (Bell, 1890) (Naldrett and Kullerud, 1967).

(b) hydrothermal processes - leaching and concentration of sulphides from a basic body by reaction with heated sol-utions emanating from depth or from nearby intrusive bodies

(Dickson, 1904).

(c)   magmatic differentiation at depth - gravitational segre-
gation of sulphides from a basic magma at depth with a
subsequent ejection as a sulphide magma (Howe, 1914).

All three hypotheses might be grouped into a single hypothesis,
namely the occurrence of magmatic differentiation in a magma
reservoir at depth. This hypothesis may be stated as the occurr-
ence of differentiation of a basic magma at depth into fractions
of acidic, basic and sulphidic composition, with ejections of such
fractions in sequence upon activation by a periodic building up of
pressure in the magma reservoir. A somewhat similar concept was
advanced by A.M. Bateman in 1917 [2] for the Sudbury area, and also
in 1951 [3] in terms of general occurrence, however, the evidence
presented within the past fifty years has not been viewed in the
perspective of this hypothesis, nor have any of the other nickel
resource-areas within the Canadian Shield since their discoveries.

As shown by Figure 1, many formations of ultrabasic rocks
containing only sparsely disseminated mineralization are known
within the Canadian Shield. A relatively smaller number have
been noted to contain concentrated nickel sulphides (Figure 2)
and only a very few formations have been more fully explored and
found to contain deposits of sufficient concentration and tonnage
to have supported mining operations under past economic conditions
(Figure 3).
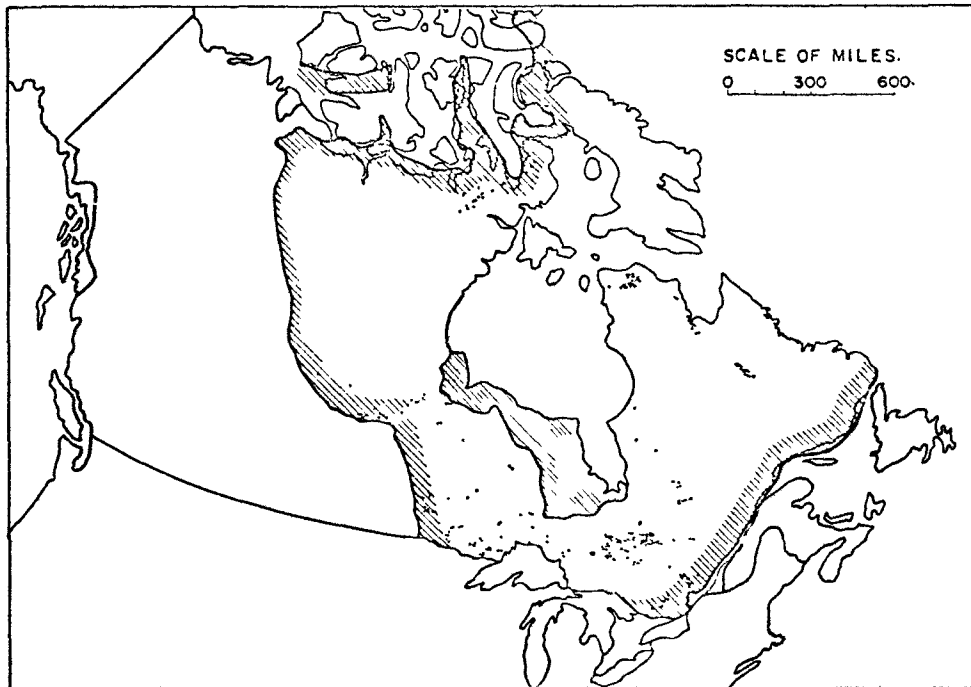
FIGURE 1. Distribution of ultrabasic rocks within the Canadian Shield. (modified after Smith, 1961)
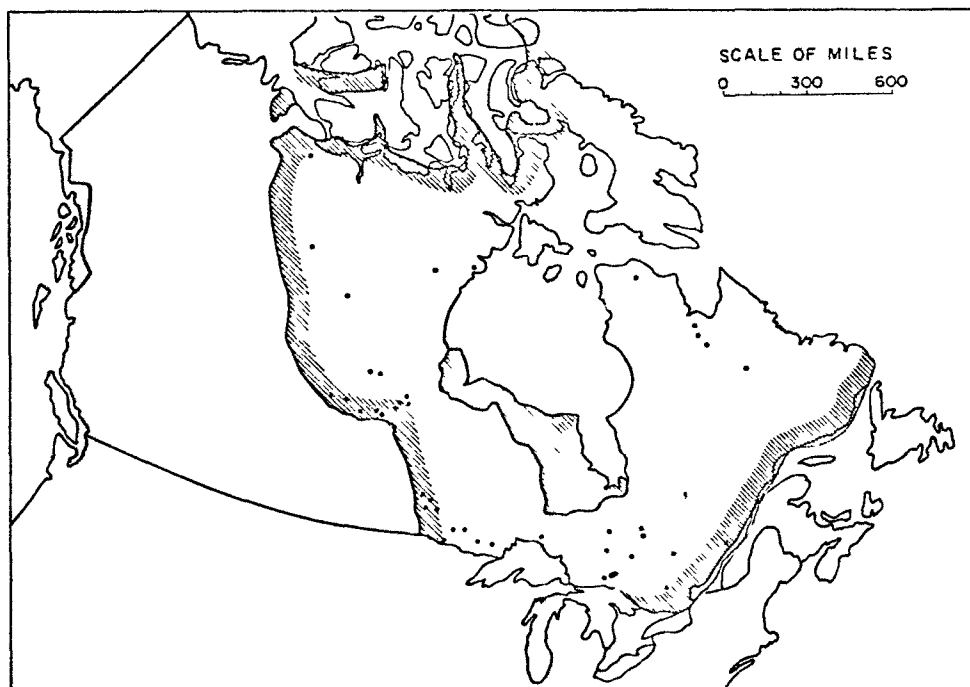
FIGURE 2. Distribution of nickel sulphide deposits related to basic intrusions within the Canadian Shield. (modified after Smith, 1961)
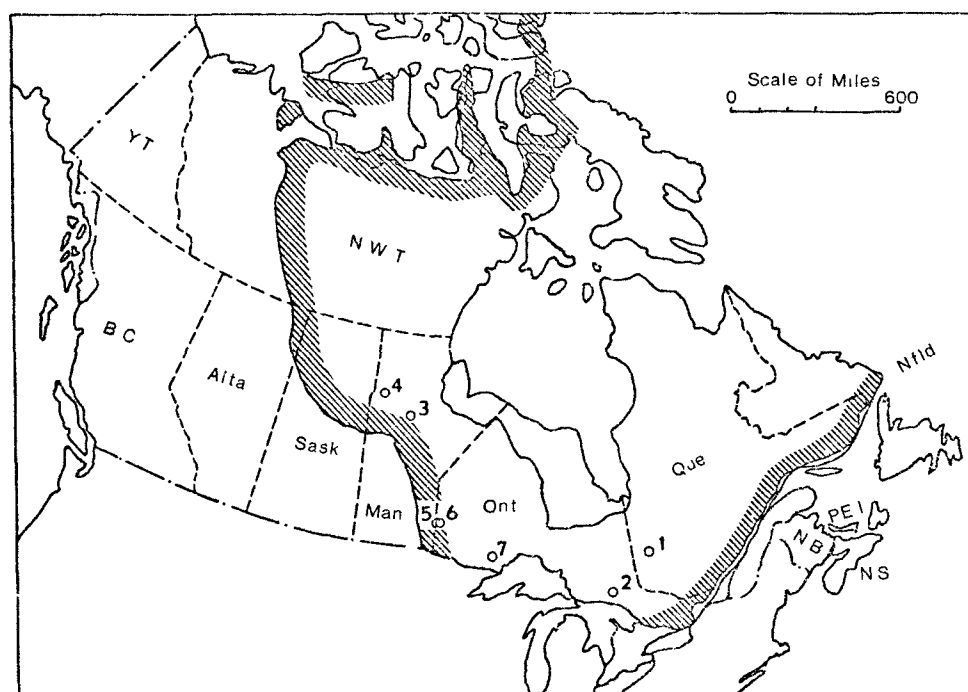
FIGURE 3. Locations of past, present and prospective nickel producing areas within the Canadian Shield.

Past Producing Area

   1 Marbridge, Malartic, Quebec

Present Producing Areas

   2 Sudbury, Ontario

   3 Moak Lake - Setting Lake, Manitoba

   4 Lynn Lake, Manitoba

   5 Bird River, Manitoba

   6 Werner Lake- Gordon Lake, Ontario

Prospective Producing Area

   7 Shebandowan, Ontario

FOOTNOTES FOR CHAPTER I

1 A.B. Yates, 1948. "Properties of the International Nickel Company of Canada" in Structural Geology of Canadian Ore Deposits, Jubilee Volume, Montreal, Canadian Institute of Mining and Metallurgy, p. 596, Montreal.

2 A.M. Bateman, 1917. "Magmatic Ore Deposits, Sudbury, Ontario," Economic Geology, Vol. 12, no. 5, p. 418.

3 A.M. Bateman, 1951. The Formation of Mineral Deposits, New York, John Wiley and Sons, p. 37.

CHAPTER II

THE SUDBURY AREA

Development of Mining

The ore deposits of the Sudbury area have been developed by basically two companies, The International Nickel Company of Canada Limited (INCO) and Falconbridge Nickel Mines Limited (FALCO). In 1887 the parent company of INCO commenced production and was joined by FALCO in 1930. [1] The following table indicates the relative scale of operations of these two companies in the Sudbury area.

Table 2

SCALE OF MINING OPERATIONS IN THE SUDBURY AREA

Company	INCO[2]	FALCO[3]
Number of operating mines	12	7
Concentrating capacity in tons of ore per day	66,500	12,800
Number of tons mined in 1968	24,350,000 *	3,208,000
Total ore reserves as of December 31, 1968	370,970,000 *	91,638,600

* - Figures inclusive of the Moak Lake-Setting Lake area

A comparison of these operations with those carried on in the other areas of study indicates the importance of Sudbury as a nickel producing area. (Table 3).

Table 3

COMPARATIVE SCALES OF MINING OPERATIONS IN THE OTHER NICKEL RESOURCE AREAS

	Lynn Lake Area [4]	Moak Lake-Setting Lake Area [5]	Bird River Area [6]	Werner Lake-Gordon Lake Area [7]	Shebandowan Area [8]
Mining Company	Sherritt Gordon Nickel Mines Ltd.	INCO	Consolidated Canadian Faraday Ltd.	Consolidated Canadian Faraday Ltd.	INCO
Commencing Year of Production	1953	1961	1969	1962	(planned production in 1972)
Number of Producing Mines	2	3	1	1	–
Concentrating Capacity in Tons per Day	4,000	15,000	700 (concentrated at Werner Lake Mill)	1,200 (including ore from Bird River Area)	2.900
Tonnage Mined in 1968	1,276,517	*	–	207,417	–
Total Ore Reserves in Tons as of December 31, 1968	12,600,000 @ 0.81% nickel & 0.40 % copper	*	1,350,000 @ 1.06 % ni. & 0.34 % cu.	593,268 @ 1.10% ni. & 0.52% cu.	(unavailable)

* - The tonnage mined and total ore reserves of the Moak-Lake-Setting Lake area are reported with the Sudbury area figures in Table 2.

Note: The Marbridge, Malartic area mines were mined out in 1968.

Problems

As evidenced by the voluminous amount of literature pub-
lished during the past eighty years, it is apparent that the
Sudbury area has aroused more interest and debate than any other
nickel resource-area in the world. An initial glance at Figure
4 would indicate a relatively simple and close spatial relation-
ship between the numerous deposits and an oval-shaped, igneous
formation known as the Sudbury irruptive. The history of the
area, however, is far from simple. Evidence gathered over the
years has suggested numerous hypotheses as explanations for such
problems as stated below.

(a) the sequence of intrusive events in the area

(b) the nature of the Sudbury irruptive - whether it was em-
     placed as a single intrusion or as two separate intrusions -
     whether it was differentiated in place or at depth

(c) the relative times and degrees of brecciation

(d) the structural shape of the irruptive at depth

(e) the genesis of the ore deposits - whether the nickel min-
     eralization was concentrated by magmatic differentiation
     from the Sudbury irruptive, by differentiation in a mag-
     matic reservoir at depth, or by hydrothermal processes

An explanation for each of these problems has been advanced in
Chapter III.

Surface Features

As shown by Figure 4, forty of the fifty-six nickel depos-
its are located around the periphery of the Sudbury irruptive
with the remaining sixteen deposits located along dykes which
appear to emanate from the irruptive in a somewhat radial
pattern. A concentric pattern of formations is expressive of
the irruptive as the outer three rings, and of extrusive form-
ations as the inner three rings. This concentric configuration,
with inward dipping borders, has suggested that the irruptive

FIGURE 4. Locations of nickel mines and deposits relative to the Sudbury irruptive.
(modified from the Report of the Royal Ontario Nickel Commission, 1917 and from The Winning of Nickel, 1967)
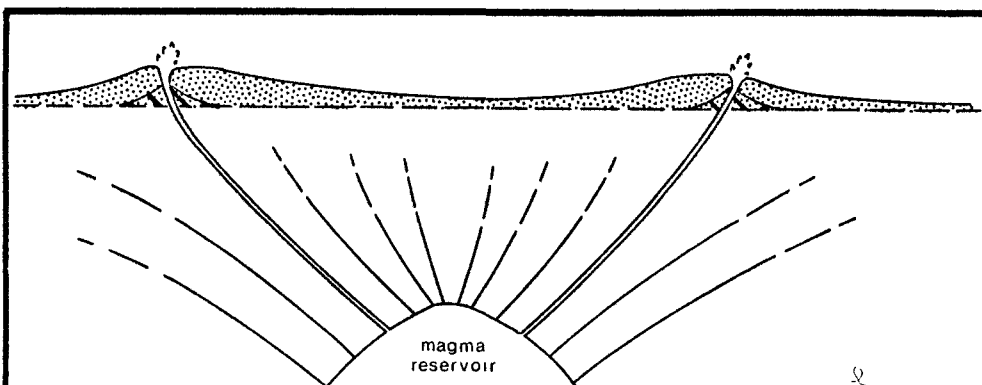
FIGURE 5. Suggested diagrammatic cross section of the Sudbury area during the pre-irruptive, extrusive period.
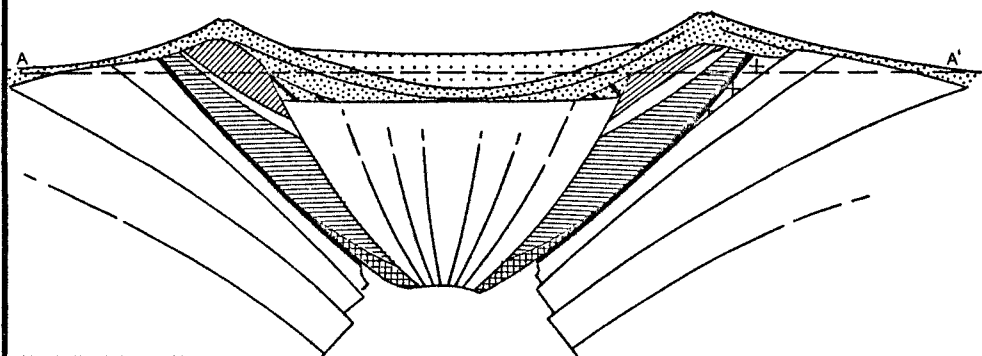
FIGURE 6. Suggested diagrammatic cross section of the Sudbury irruptive prior to late faulting and erosion.

FIGURE 8. Geological map of the Sudbury irruptive and associated formations. (modified after Speers, 1957, Sopher, 1963 and Stevenson, 1963)

— — Fault
········· Major bands of breccia
➤45 Dip of the outer contact of the Sudbury irruptive
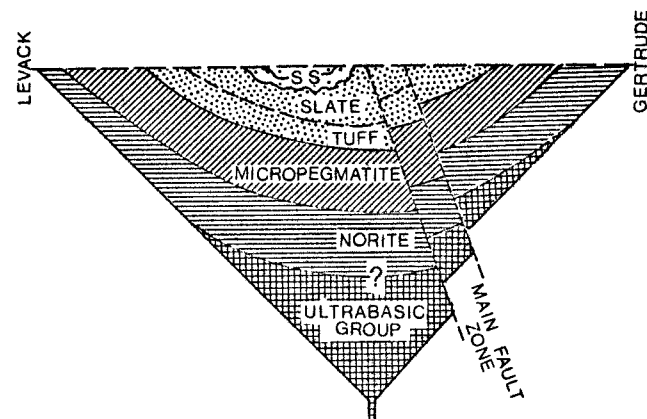
FIGURE 7. Diagrammatic cross section of the Sudbury irruptive. (after Wilson, 1956)

LEGEND

Quartz diorite

Granite

Ultrabasic zone

Norite

Hybrid zone   } Sudbury irruptive

Micropegmatite

Bedded volcanic tuff

Volcanic tuff

Quartzite breccia

Gabbro

Gneiss and granite

Quartzite

Greywacke, acidic and basic volcanic rocks

FIGURE 8. Geological map of the Sudbury irruptive and associated formations. (modified after Speers, 1957, Sopher, 1963 and Stevenson, 1963)

— — Fault
········· Major bands of breccia
➤ 45 Dip of the outer contact of the Sudbury irruptive

Volcanic tuff
Quartzite breccia
Gabbro
Gneiss and granite
Quartzite
Greywacke, acidic and basic volcanic rocks

Scale of Miles
0   5

Detail Area
Figure 9
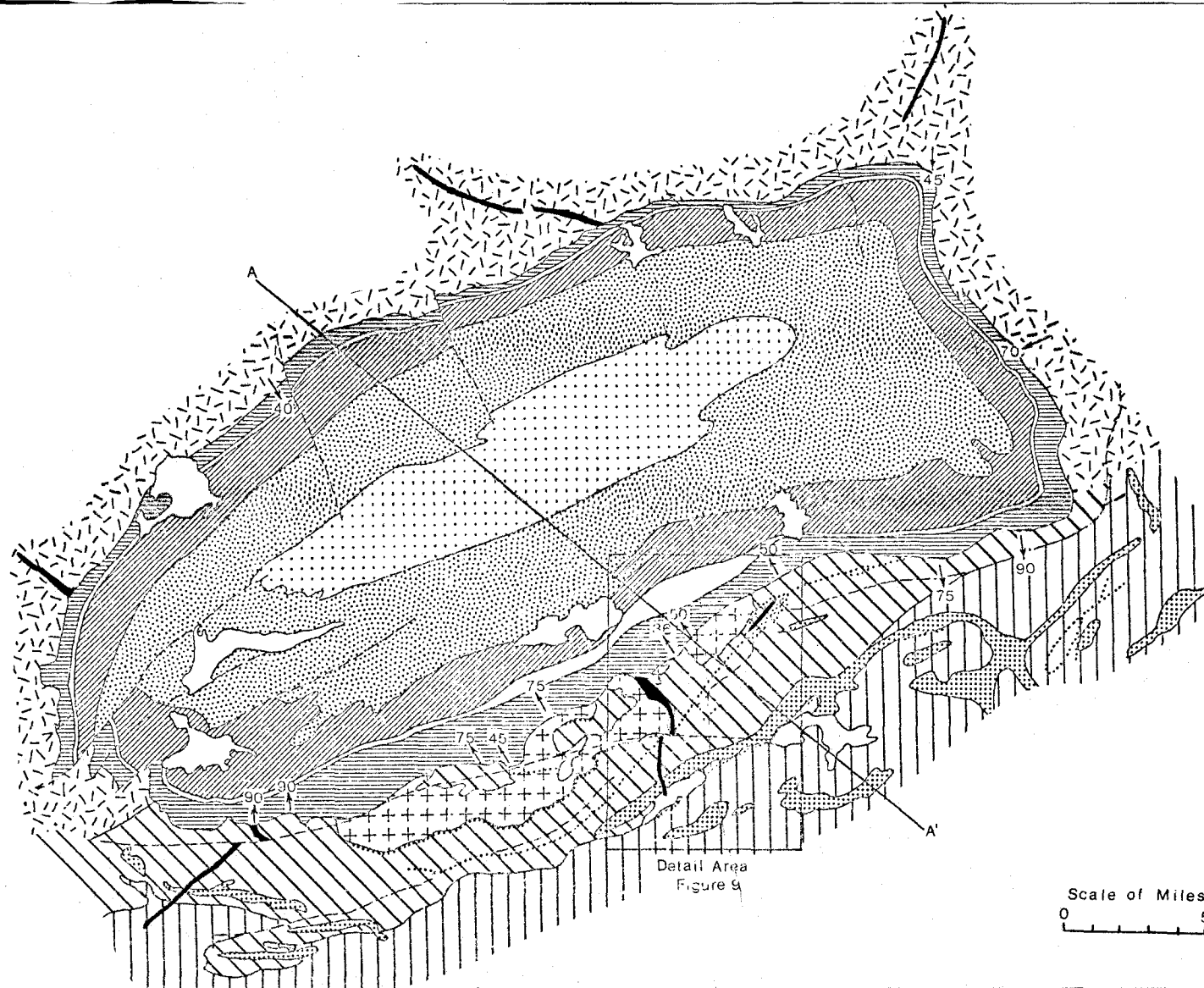
has a basin-shape at depth. Consequently, this inferred structure
has become commonly referred to as the Sudbury Basin. A basin-
shape is similarily expressed as a surface feature by a relatively
flat, drift-covered valley enclosed by a ring of rugged hills, 100
to 200 feet in height. In surface dimensions the irruptive is 37
miles long, 17 miles wide, and 1 to 3.6 miles broad.

Composition of the Formations

As exposed on the surface, the three rings of the irruptive
are composed of an inner ring of acidic rock, termed micropeg-
matite (Walker, 1897), a narrow zone of mixed acidic and basic
composition, and an outer ring of basic rock, termed norite
(Walker, 1897), a gabbro containing the mineral hypersthene. The
radial dykes, which appear to emanate from the norite-ring of the
irruptive, were considered by Coleman (1903) to be integral but
offset portions of the norite. Consequently he termed the dykes
offsets. These five offsets and other narrow intrusives found
along the margin of the irruptive are composed of quartz diorite,
a noritic intrusive rock more basic in composition than the norite,
and also the rock type with which the nickel sulphide ores appear
to be spacially related.

The inner periphery of the irruptive consists of a 200 to
500-foot wide border strip of quartzite breccia, followed in-
ward by roughly concentric rings of volcanic tuff, a slaty variety
of tuff, and a sandy, bedded tuff. [9]

Structure of Depth

The outer contact of the irruptive has been noted to dip
inward at angles ranging from 30 to 75 degrees (Figure 8), with
the exceptions of the far southwestern and southeastern segments
which vary from vertical dips to outward dips of 65 degrees. [10]
A palaeomagnetic study by Sopher (1963) has indicated that the
Sudbury Basin was rotated through a total of 40 degrees by late

faulting, however all of the original contacts prior to fault-
ing were considered to dip inwards at angles of 30 to 90 de-
grees. [11]   Such steeply dipping, original contacts disprove
Collin's hypothesis (1935) of the irruptive as a horizontal
sill which was later folded, but basically leave the following
two hypotheses of emplacement open to conjecture and further
evidence.

(a)   intrusion of the irruptive around a down-faulted block
      (Knight, 1917). [12]

(b)   intrusion of the irruptive as a funnel-shaped body
      (Wilson, 1956). [13]

The feasibility of the latter hypothetical model (Figure 7) is
open to question as Wilson did not offer a seemingly adequate
explanation for the vast amount of country rock which would have
to be displaced by a funnel-shaped intrusion. Knight's hypo-
thesis of intrusion around a downfaulted block carries the
implication that a minimum amount of country rock would have
to be displaced in order to accomodate the volume of the
intrusion (see Figure 6).

History of the Sudbury Area

The following sequence of events is proposed by the writer
as an overall perspective of the probable origin and manner of
emplacement of the Sudbury irruptive and its associated nickel
deposits. Evidence gathered by the many investigators of the
Sudbury area, is presented and re-evaluated, taking into con-
sideration modified and more extensive views of Knight's hypo-
thesis for the emplacement of the irruptive (as stated above)
and Bateman's hypothesis of the concentration and emplacement
of the nickel deposits (see page 4).

Table 4

SUMMARY OF THE HISTORY OF THE SUDBURY AREA

- period of mountain-building
- intrusion of a magma of basic composition into the mountain-core

Pre-irruptive Period

(1a) intrusion of acidic composition, granite

(1b) intrustion of basic composition, quartz gabbro

(1c) intrusion of more basic composition, porphyritic olivine diabase

- formation of major tension fractures, faults and brecciation

(2a & b) extrusion of volcanic breccia and tuff of an intermediate composition, andesite

Intrustion of the Irruptive

(3a) intrustion of acidic composition, micropegmatite

(3b) intrusion of basic composition, norite with very minor, disseminated mineralization

Post-irruptive Period

(4a) intrustion of acidic composition, granite

(4b) intrustion of basic composition, quartz diorite

(4c) intrusion of more basic composition, quartz diorite with inclusions of ultrabasic composition and disseminated mineralization

(5a) intrusion of acidic composition, aplite

(5b) intrusion of basic composition, trap rock

(5c) formation of tension fractures and faults, with moderate brecciation, hydrothermal activity, and emplacement of minor amounts of basic minerals and probable moderate amounts of mineralization

(6a)   intrusion of acidic composition, aplite, quartz and also
       carbonate

(6b)   minor emplacement of basic composition, the minerals of
       hornblende and biotite immediately prior to or with the
       massive sulphide mineralization

(6c)   intrusion of massive nickel sulphide mineralization

(6d)   intrusion of carbonate and late mineralization

Pre-irruptive Period

Roughly 1.8 to 2 billion years ago,[14] the Sudbury area
was uplifted, folded and faulted during a period of mountain-
building. [15] The area of granite and granite gneiss, bordering
the northern and eastern ranges of the present site of the
irruptive (Figure 8), has been considered to have been emplaced
during or prior to this period of mountain-building. [16]

A magma of basic composition is suggested as having welled
up into the mountain core. With possible proportions of bathol-
itic size and miles of overlying and insulating country rock, such
a magma would be subject to a slow rate of cooling and crystall-
ization, with a probable partial segregation of the magma into
an upper acidic fraction, a lower basic fraction, and a still
lower sulphidic fraction. Such a process of segregation, termed
magmatic differentiation, envisions the heavy, basic minerals
of iron and magnesium content as being the first to crystallize
and sink into the liquid magma, leaving an upper, residual,
magmatic fraction of more acidic composition. [17]

Events (1a), (1b) and (1c)

By a gradual building up of pressure, caused possibly
by crystallization and accumulation of volatile gases, a minor
portion of the partially differentiated magma was tapped off
along faults and sheared bedding planes of the overlying country
rock. The first intrusive event was in intrusion of grey granite,
noted at the Hardy mine (northern range, Figure 4), as being

intruded in turn by quartz gabbro. [18] South of the irruptive,
numerous sills and dykes of the quartz gabbro are exposed and
noted by Cooke (1946) to have been in turn intruded by dykes of
porphyritic olivine diabase. [19] A post-orogenic age for these
three intrusives has been indicated by evidence of only minor
shearing and brecciation, with a pre-irruptive age indicated by
a cross-cutting relationship of the irruptive with the latest
intrusion, the porphyritic olivine diabase. [20]

Event (2a and b)

Following this first sequence of events, extreme pressure
apparently built up in the magma reservoir. The consequence of
such pressure bearing on the overlying country rock may be
viewed in the perspective of Anderson's theory of cone-sheet
development. [21] As indicated by Figure 5, a hypothetical cross
section, the hydrostatic pressure of the magma, by exceeding the
lithostatic pressure of the overlying country rock, could develop
a set of radiating tension fractures or fissures along paths of
the greatest principal stress axes. At such time that a number of
these fractures had been extended to the surface of the earth,
the consequent release of pressure resulted in the expulsion of
brecciated country rock and vent agglomerate. In turn, vast
quantities of volcanic tuff of an andesitic composition were
extruded and accumulated on surface to heights of thousands of
feet. [22] Pulsations of pressure accompanying such violent ex-
trusions resulted in the formation of highly brecciated zones
along tension fractures which had not been extended to the
surface. With a gradual depletion of magma in the reservoir and
an increasing volume of extruded tuff on the surface, it is
suggested that a U-shaped segment of the earth's crust, largely
outlined by intersecting tension fractures, gradually subsided
some thousands of feet in depth.

Intrusion of the Irruptive, Events (3a) and (3b)

Following the volcanic activity, pressure once again built
up in the magma reservoir. A large proportion of the remaining
magma was forcefully intruded around the periphery of the down-
faulted block as basically two separate intrusions closely re-
lated in time. As suggested by Figure 6, a hypothetical cross
section of the irruptive at depth, an acidic fraction of the
magma occupied the upper portion of the intruded area as a
steeply dipping layer which upon consolidation formed the
irruptive's inner ring of micropegmatite (Figure 8). A major
portion of the intruded magma was composed of a basic fraction
which subsequently consolidated as an underlying layer (Figure 6),
and as the irruptive's outer ring of norite (Figure 8). A zone
of mixed acidic and basic composition, lying between the steeply
dipping layers of micropegmatite and norite (Figure 6), is
considered as representative of an intermingling of the two
fractions during intrusion and partially of further differen-
tiation of the two fractions in place following the intrusion
(see pages 38 and 39). At depth, the norite similarily under-
went differentiation in place following the intrusion with the
evolution of an underlying zone of ultrabasic composition as
suggested by Figure 6. Evidence of such a differentiated zone
has been indicated by a later intrusion composed of quartz
diorite which apparently brecciated this zone upon intrusion
and carried upwards in suspension such ultrabasic fragments as
olivine gabbro, olivine, norite, pyroxenite, and dunite. [23]
The average chemical compositions of the volcanic tuffs,
micropegmatite and norite are indicated by Table 5.

Post irruptive Period

The post-irruptive period may be viewed as three sub-
periods, each consisting of an acidic intrusive event followed
by one or more basic intrusive events.

Table 5

CHEMICAL COMPOSITIONS OF IGNEOUS FORMATIONS

Chemical Composition	I Acid Offset Dyke	II Micro-pegmatite	III Complex	IV Volcanic Tuffs	V Norite	VI Quartz Diorite Offset Dykes
SiO_2	71.45	67.83	63.14	65.9	55.16	58.55
Al_2O_3	12.17	13.36	14.65	11.6	16.86	15.75
Fe_2O_3	1.03	1.28	1.52	1.7	1.94	2.16
FeO	4.18	4.39	5.17	4.9	6.50	6.41
CaO	1.35	2.04	4.03	2.7	7.42	6.15
MgO	0.94	1.50	2.85	3.6	5.17	4.07
Na_2O	3.06	3.39	3.20	3.5	2.87	2.63
K_2O	3.49	3.82	2.91	2.9	1.35	2.07
H_2O	1.06	1.21	1.24	1.8	1.28	1.06
TiO_2	0.79	0.68	0.74	0.4	0.83	0.83
P_2O_5	0.66	0.21	0.23	0.1	0.25	0.27
S	0.08	0.05	0.08		0.12	0.23
MnO	0.13	0.07	0.08	0.2	0.10	-
CO_2	-	0.17	0.16	0.3	0.15	0.05
Total	100.39	100.00	100.00	99.6	100.00	100.23
Specific Gravity	2.697	2.710	2.766		2.855	2.875

I - analysis of single dyke intruded into volcanic tuffs from micropegmatite (Collins, 1934, p. 175)
II, III, and V - average of 34 analyses of micropegmatite, of combined analyses of micropegmatite and norite, and of 38 analyses of norite (Collins, 1934, p. 172)
IV - average of 5 analyses of volcanic tuffs (Burrows & Rickaby, 1934, pp. 10, 14, 22), (Thomson, 1957, p. 18)
VI - averages of all available analyses of offset dykes by 1934 (Collins, 1934, p. 172)

Event (4a)

As the first intrusive event, a granitic magma was
intruded along the southern and northern flanks of the irruptive. [24]
As shown by Figure 8, the largest exposed mass, known as the
Creighton granite, lies along the southern range for a distance
of twelve miles. To the northeast, a half-mile long body repre-
sents the Lady Violet granite, and a three-mile long body repre-
sents the Murray granite. Ginn (1958), in his study of the Sudbury
area granites, found the Creighton and Murray granites to be
"remarkably similar in chemical composition" and also very
similar to the Lady Violet granite, thereby substantiating a
genetic relationship (see Table 6). [25] Granites of such age
have been also noted by Yates (1948) to occur along the northern
range, however, their configurations were not fully mapped. [26]

The age relationship between these granites and the
irruptive has been the subject of considerable rationalization
by some investigators in attempts to accomodate their theories
with a pre-irruptive age for the granites. Investigations, by
such men as Knight (1917), Phemister (1925), Burrows and Rickaby
(1934), and Yates (1938 & 1948), have substantiated a post-
irruptive age for these granites without recourse to considerable
rationalization. Of the three main phases of the Creighton
granite, at least two dykes of the earliest phase, a porphyritic
coarse-grained granite, were noted as having been intruded into the
norite of the irruptive. [27] Numerous to hundreds of dykes of
the latest phase, a medium to fine-grained granite, were noted
as being intruded into the norite between the Creighton and Crean
Hill mines. [28] The intrusive nature of the Murray granite,
similar in texture to the youngest phase of the Creighton granite,
can be best described by the statement of Yates (1938) that "the
granite has unquestionably brecciated, intruded, and altered the
norite and includes fragments of it." [29] Both dykes and small
masses of granite, similar to the Murray type of granite, were

Table 6

CHEMICAL COMPOSITIONS OF GRANITES

Chemical Composition	Creighton Granite	Murray Granite	Lady Violet Cranite
SiO_2	74.44	73.78	73.34
Al_2O_3	11.20	11.70	10.60
Fe_2O_3	2.22	2.57	1.05
CaO	1.35	1.30	0.35
MgO	0.49	0.25	0.30
Na_2O	2.95	3.35	4.69
K_2O	5.03	5.18	7.91
$+H_2O$	0.45	0.38	0.06
$-H_2O$	0.05	0.05	0.02
MnO	0.03	0.03	-
TiO_2	0.17	0.17	0.05
Total	98.38	98.76	98.37

Source: R.M. Ginn, 1958. A Study of the Granitic Rocks in the Sudbury Area, Unpublished M.S. thesis, Queen's University, Kingston.

noted to occur within the norite at distances of over two
miles from the main masses of granite south of the irruptive.[30]
Narrow stringers of a similar granite were also noted by Phemister
(1925) to intrude the micropegmatite, thereby indicating both
post-micropegmatite and post-norite ages for the granites. [31]

Event (4b)

The basic intrusive, quartz diorite, which followed the
intrusion of the granites, has been described as medium to
fine-grained, less altered than the norite, and with a more
basic composition than the norite. [32] This more basic comp-
osition has also been shown by chemical analyses of samples
taken from 4 of the 5 offset dykes (see Table 5, page 19).
Prior to, or during the intrusion, there appears to have been
a doming up of both the irruptive and its surrounding area,
such that the quartz diorite was injected as thin bodies around
much of the circumference of the irruptive and also as thin off-
set dykes along apparent tension fractures which radiated out-
ward from the irruptive for distances as great as nine miles
(Figure 8).

Evidence which establishes both a post-irruptive and a
post-granite age for the intrusion of the quartz diorite is
presented as follows.

Evidence of a Post-norite Age

(a) At the Murray mine (Figure 4, southern range), dykes of
quartz diorite were intruded into the norite, with one six-foot
wide dyke noted to exhibit sharp and contrasting contacts
against the coarser grained, marginal phase of the norite. [33]

(b) Near the Levack mine (Figure 4, northern range), a dyke of
quartz diorite was noted by Collins (1934) to have been
intruded well into the irruptive, cutting the norite, the
hybrid zone of mixed acidic and basic composition, and also
the micropegmatite. [34]

Evidence of a Post-granite Age

(a) The quartz diorite of the Copper Cliff offset is shown
by Figure 9 to cut the eastern edge of the Creighton granite.
Yates (1938) observed that it "is strongly chilled against the
granite over a width of 2 or 3 inches; it also cuts a faintly
defined gneissic structure at a small angle; [and] small tongues of
the diorite extend out into the granite." [35]

(b) As also shown by Figure 9, dykes of Murray granite extend
southward toward the Frood breccia zone. Dykes of this granite
were observed on the southern side of the breccia zone with
fragments of granite noted in the breccia but not in the lenses
of quartz diorite. [36]

Event (4c)

        Naldrett and Kullerud (1967), in a recent study at the
Strathcona mine (northern range), have presented evidence that
indicates the occurrence of two intrusions of quartz diorite
rather than just one, however both were shown to be closely
related in both time and space (Figure 10). The later in-
trusion differed from the earlier intrusion by having a finer
grained texture, little quartz, an absence of micrographic
quartz and feldspar, and also inclusions of ultrabasic com-
position. [37] Such inclusions have been identified by Cowan
(1967), and noted in order of greater ultrabasic composition
as olivine gabbro, olivine norite, pyroxenite and dunite. [38]
Occurrences of such inclusions have also been observed by Souch,
Podalsky et al and noted by Naldrett and Kullered (1967)
"to occur in sulfide ore and in younger intrusions at numerous
localities around the margin of the Nickel Irruptive." [39]
The absence of any exposed intrusions of such ultrabasic com-
position in the Sudbury area has been proposed as evidence that
these inclusions represent fragments from a zone of ultrabasic
rocks lying along the base of the irruptive at some unknown
depth. [40] A possible configuration of such a zone has been
suggested in Figure 6.
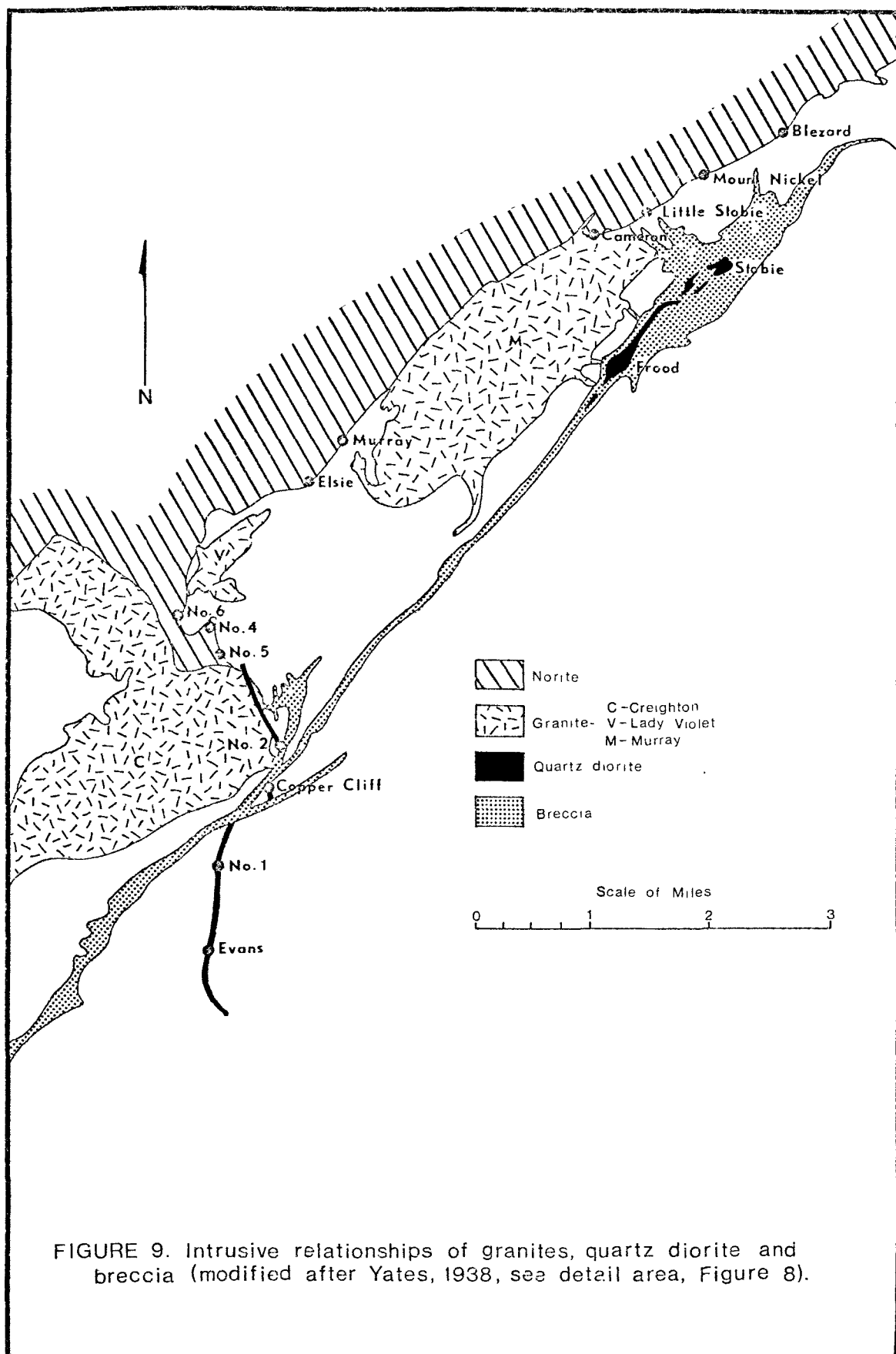
FIGURE 9. Intrusive relationships of granites, quartz diorite and breccia (modified after Yates, 1938, see detail area, Figure 8).

MICROPEGMATITE
and
HYBRID ZONE

NORITE

Scale of Feet
0   200   400   500   600

LEGEND

Ore zones

Breccia hanging wall
         foot wall

Quartz diorite (more basic with ultrabasic inclusions)

Quartz diorite

Footwall mafic and granite gneiss
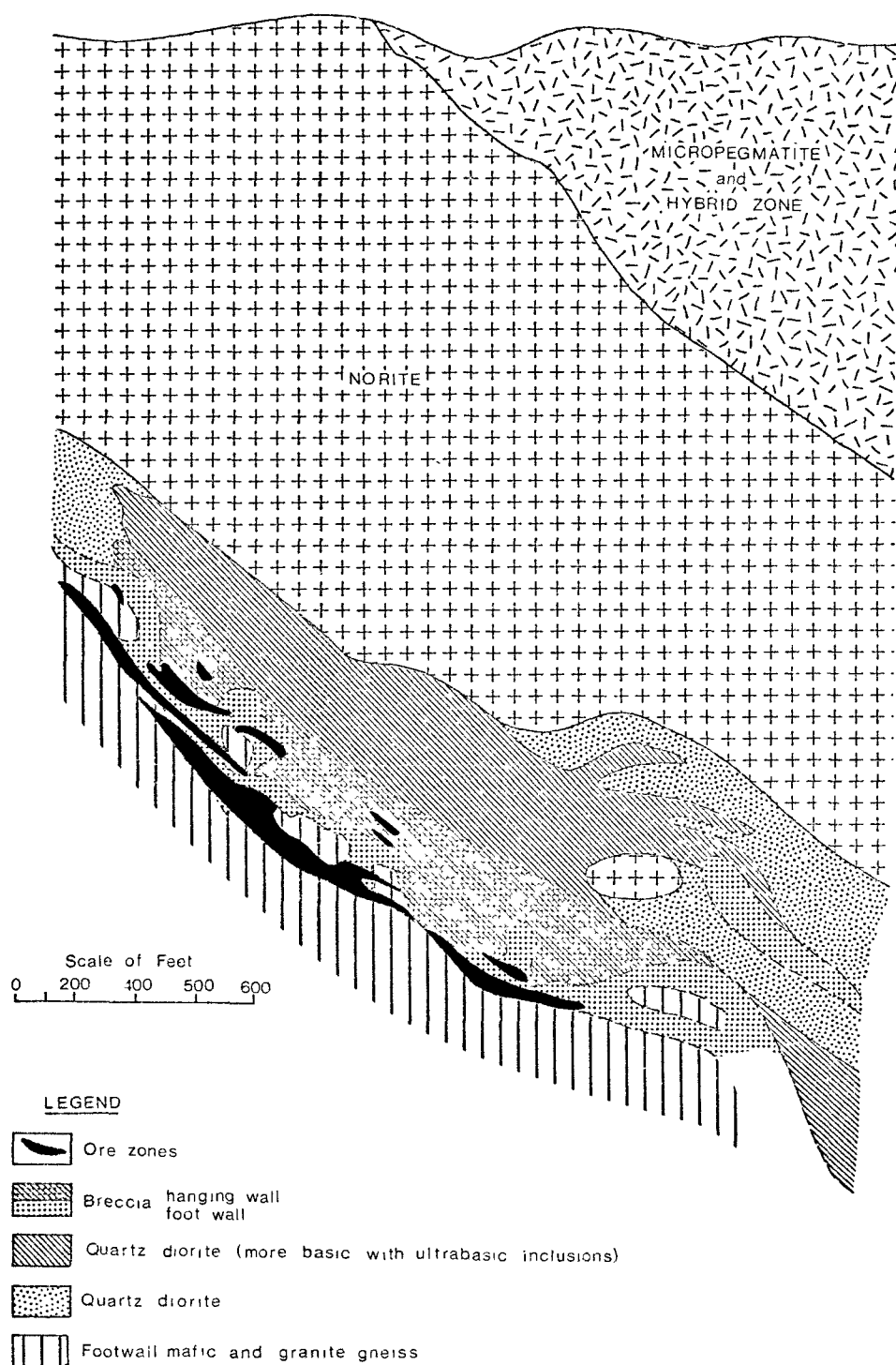
FIGURE 10. Cross-section of the Strathcona mine showing intrusive relationships of quartz diorites, breccias and ore zones (modified after Naldrett and Kullerud, 1967)

Events (5a) and (5b)

Following the intrusions of quartz diorite, small aplite
and trap dykes were emplaced, as indicated in the sequences
of events presented by Yates (1938) and Fairbairn and Robson
(1942). [41] Aplite was noted to cut both the quartz diorite
of the Copper Cliff offset and the Creighton granite, however
reference to an apparent age relationship between the aplite
and trap dykes was not located by the writer. [42] A later
intrusive age for the trap rock, relative to the aplite, might
be inferred from the observations of Cooke (1946) that these
fine-grained uralitic diabases both cut and are cut by breccia,
thereby indicating a close relationship with the following period
of brecciation. [43] Relative to the preceding intrusives, Cooke
also noted that the trap dykes cut the quartz diorite, the
Creighton and Murray granites, and the norite.

Event (5c)

Event (5c) may be considered as consisting of a number of
occurrences closely related in time and space; namely the
occurrences of faulting, brecciation, hydrothermal activity, and
the emplacement of sulphide mineralization with minor basic
minerals.

As shown by Figure 8, a following period of extensive
faulting cut the irruptive into segments, cut through the
Creighton granite, and displaced the quartz diorite of both the
Copper Cliff and Worthington offset dykes. Specific references
to locations of cross-cutting relationships between the faults
and the dykes of aplite and trap rock have not been located,
however, both Yates (1938) and Fairbairn and Robson (1942)
have listed faulting as a following event relative to these
minor dyke-rocks. [44] At the Falconbridge mine (southeast
corner of the irruptive), the relationships between the fault-
ing and the following brecciation are apparent (Figure 11).
The initial faulting altered the adjacent wall rock to a chlorite

Plan of Level

A — south — LEVEL — north — A'

LEGEND

Massive sulphides

Breccia sulphides

Jasperoid

Irregular zone of silicified greenstone greenstone and jasperoid

Schist (chlorite)

Norite

Greenstone (not silicified)

Main shear

Scale of Feet

0   50   100   200
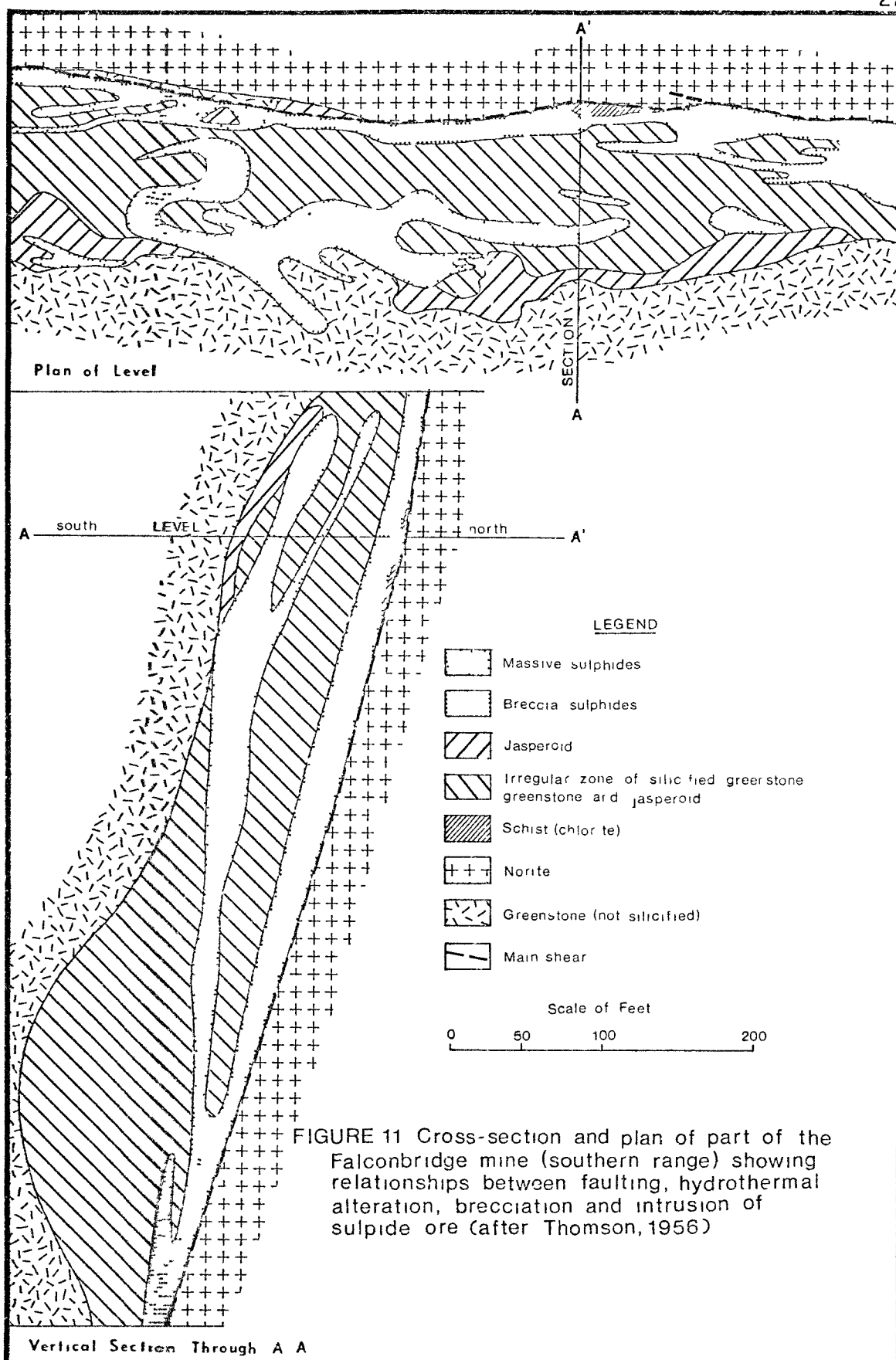
FIGURE 11 Cross-section and plan of part of the Falconbridge mine (southern range) showing relationships between faulting, hydrothermal alteration, brecciation and intrusion of sulpide ore (after Thomson, 1956)

Vertical Section Through A A

schist, served as an avenue for silica-rich solutions which silicified the norite and greenstone, and formed later, quartz carbonate veins. As noted by Lochhead (1955), the following brecciation incorporated as fragments "well-preserved small drag folds, schisting, silicification, and quartz carbonate veining". [45] Burrows and Rickaby (1934) observed that varying quantities of quartz and calcite were present at all of the ore deposits known in 1934, however such emplacement preceded the brecciation and the later intrusion of massive sulphides, as indicated by the relationships noted by Knight (1917) and Clarke and Potapoff (1959). [46]

The brecciation, which followed the faulting, occurred close to the outer contacts of the irruptive and also along pre-irruptive zones of brecciation as much as three miles south of the irruptive's southern contact (Figure 8). The following evidence is presented as indicative of a post-irruptive age for this breccia which was:

(a) noted to be intrusive into the norite at the Levack mine (northern range); [47]

(b) noted to cut and include fragments of the Creighton and Murray granites; [48]

(c) noted to cut the Frood and Copper Cliff offsets of quartz diorite, and also the quartz diorite present at many of the mines located around the periphery of the irruptive; [49]

(d) noted to cut the latest intrusion of quartz diorite at the Strathcona mine (northern range); [50]

(e) and noted by Knight (1917) and Yates (1948) to be associated with fault zones at numerous localities along the southern range.

Accompanying the faulting and brecciation, hydrothermal solutions altered the plagiclase feldspar in the fragments to a more sodic composition, [51] and added the secondary minerals of chlorite, epidote, biotite and quartz. [52] A characteristic feature of such breccia was the presence of rounded 'eyes' or

porphyroblasts of quartz and feldspar. [53] Despite the relatively
close spatial association of breccia and ore zones, this meta-
somatic alteration of the breccia was apparently not a product
of hydrothermal solutions accompanying the intrusion of massive
sulphide mineralization. Evidence for such an observation is
suggested by the occurrences of metasomatically altered breccia
found by Speers (1956) along the eastern and northern ranges to
be barren of sulphide mineralization. [54] There is evidence,
however, that a significant portion of the disseminated mineral-
ization found in the various breccias may have been introduced
along with basic minerals following the hydrothermal alteration
of the breccia. At the Strathcona mine, Cowan (1967) observed
that:

> " In other areas where disseminated mineralization is
> intense, the breccia matrix is darker in colour and
> contains abundant small mafic patches and crystal
> fragments ... in some locations the dark breccia
> appears to show cross-cutting relations." [with
> the lighter-coloured breccia] [55]

Events (6a) and (6b)

In turn the breccia was noted to be cut by minor aplite
dykes in the area of the Creighton granite and also at the
Strathcona mine (northern range). [56]

The intrusion of massive sulphide mineralization, which
followed, apparently carried with it or was immediately pre-
ceded by minor amounts of hornblende and biotite. At the
Creighton mine, blocks of Creighton granite were noted by
Wandke and Hoffman (1924) to show "a black rim of hornblende
and biotite which separates the unaltered granite from the
encroaching sulphides". [57] Cowan (1967) also observed rims
of hornblende and biotite around basic fragments at the Strath-
cona mine. [58] The small basic patches and crystal fragments
noted to occur within the late breccia at the Strathcona mine
(as quoted above)   are suggestive of the probability that both

the disseminated and massive sulphide mineralization were
emplaced with varying amounts of hornblende and biotite.

Event (6c)

A study of the published reports concerning the Sudbury
area mines indicates that the massive sulphide mineralization
was forcefully injected along faults, fissures, and associated
zones of shearing and brecciation in virtually any rock type.
Dependent upon the types of host rocks and structure, the ore
deposits are represented as combinations of massive sulphide
zones, sulphide stringers or disseminated sulphides. All of
the Sudbury deposits contain a characteristic assemblage of the
sulphide minerals pyrrhotite $Fe_{1-x}S$, pentlandite $(Fe,Ni)S$, and
chalcopyrite $CuFeS_2$. [59]

Event (6d)

Varying types of late mineralization have been reported
to occur around the irruptive. Millerite, NiS, the iron-
deficient mineral of nickel, has been observed at the Vermillion
and Strathcona mines. [60] Arsenides of nickel were also noted
at the Falconbridge, Vermillion and Frood-Stobie mines. [61]
At the Falconbridge mine, the massive sulphide ores have been
intersected by numerous cross-fractures carrying the sulphide
minerals of sphalerite, galena, marcasite, and also carbonates. [62]
Hydrothermal alteration was observed in association with the
late mineralization at the Falconbridge and Strathcona mines.

FOOTNOTES FOR CHAPTER II

1 B.W. Mackenzie, 1968, <u>Nickel-Canada and the World</u>, Ottawa, Department of Energy, Mines and Resources, Mineral Report 16, pp. 3 and 60.

2 <u>Canadian Mines Handbook</u>: <u>1969-1970</u>, ed. by H.S. Myers, Toronto, Northern Miner Press, 1969, pp. 182-83.

3 <u>Ibid</u>., pp. 141-43.

4 <u>Ibid</u>., p. 323.

5 <u>Ibid</u>., p. 182.

6 <u>Ibid</u>., p. 131.

7 <u>Ibid</u>., pp. 49 and 99.

8 <u>Ibid</u>., p. 182.

9 A.B. Yates, 1948, "Properties of the International Nickel Company of Canada", in <u>Structural Geology of Canadian Ore Deposits</u>, Jubilee Volume, Montreal, Canadian Institute of Mining and Metallurgy, p. 599.

10 S.R. Sopher, 1963, <u>Palaeomagnetic Study of the Sudbury Irruptive</u>, Geological Survey, Canada, bull. 90, map facing p. 1.
    E.C. Speers, 1957, "The Age Relation and Origin of Common Sudbury Breccia," <u>Journal of Geology</u>, vol. 65, p. 499.

11 Sopher, 1963, <u>op. cit</u>., pp. 22-23.

12 Knight, 1917, <u>op. cit</u>., p. 122.

13 H.D.B. Wilson, 1956, "Structure of Lopoliths," <u>Bulletin of the Geological Society of America</u>, vol. 67, pt. 1, p. 297.

14 H.W. Fairbairn, P.M. Hurley and W.H. Pinson, 1960, "Mineral and Rock Ages of Sudbury-Blind River, Ontario," <u>Proceedings of the Geological Association of Canada</u>, vol. 12, pp. 41 and 56.

15 H.C. Cooke, 1946, <u>Problems of Sudbury Geology</u>, Geological Survey, Canada, bull. no. 3, p. 16.

16 Ibid., p. 9.

17 A.M. Bateman, 1951, The Formation of Mineral Deposits, New York, John Wiley and Sons, p. 38.

18 G.P. Mitchell and A.D. Mutch, 1957, "Hardy Mine" in Structural Geology of Canadian Ore Deposits, Congress Volume, vol. 2, Montreal, Canadian Institute of Mining and Metallurgy, pp. 352-53.

19 Cooke, 1946, op. cit., p. 58.

20 Cooke, 1946, op. cit., pp. 58-59.

21 E.M. Anderson, in E.B. Bailey et al, 1924, "The Tertiary and Post-Tertiary Geology of Mull, Loch Aline, and Oban," Memoir Geological Survey of Scotland, in M.P. Billings, 1954, Structural Geology, New Jersey, Prentice-Hall, p. 314.

22 R.S. Dietz, 1962, "Sudbury Structure as an Astrobleme," Journal of Geology, vol. 72, 1964, pp. 429-30.

23 A.J. Naldrett and G. Kullerud, 1967, "A Study of the Strathcona Mine and Its Bearing on the Origin of the Nickel-Copper Ores of the Sudbury District, Ontario," Journal of Petrology, vol. 8, pt. 3, p. 493.
    J.C. Cowan, 1967, "Geology of the Strathcona Ore Deposit," Canadian Mining and Metallurgical Bulletin, vol. 1, no. 669, 1968, p. 43.

24 A.B. Yates, 1938, "The Sudbury Intrusive," Transactions of the Royal Society of Canada, vol. 32, sect. 4, p. 172.

25 R.M. Ginn, 1958, A Study of the Granitic Rocks in the Sudbury Area, Unpublished M.S. Thesis, Queen's University, Kingston, p. 73.

26 Yates, 1948, op. cit., p. 600.

27 Yates, 1938, op. cit., pp. 167-68.

28 Knight, 1917, op. cit., p. 141.
    A.G. Burrows and H.C. Rickaby, 1934, "Sudbury Nickel Field Restudied," Department of Mines, Ontario, vol. 43, pt. 2, 1935, p. 30.
    Yates, 1948, op. cit., p. 30.

29 Yates, 1938, op. cit., p. 168.

30 T.C. Phemister, 1925, "Igneous Rocks of Sudbury and their Relation to the Ore Deposits," Department of Mines, Ontario, vol. 34, pt. 8, 1926, pp. 9, 10, 13, 14, and 17.
    Yates, 1948, op. cit., p. 600.

31 Phemister, 1925, op. cit., p. 29.

32 Yates, 1948, op. cit., p. 605.
    Naldrett and Kullerud, 1967, op. cit., pp. 463 and 491.

33 Yates, 1938, op. cit., p. 162.

34 W.H. Collins, 1934, "Life History of the Sudbury Nickel Irruptive," Transactions of the Royal Society of Canada, vol. 28, sect. 4, p. 162.

35 Yates, 1938, op. cit., p. 167.

36 Ibid., pp. 168-69.

37 Naldrett and Kullerud, 1967, op. cit., p. 492.

38 Cowen, 1967, loc. cit.

39 B.E. Souch, T. Podalsky and Geological Staff of the International Nickel Co. of Canada Ltd., The Sulfide Ores of Sudbury: Their Particular Relation to a Distinctive Inclusion-Bearing Facies of the Nickel Irruptive, Unpublished Study, in Naldrett and Kullerud, 1967, op. cit., p. 490.

40 Naldrett and Kullerud, 1967, op. cit., p. 453.

41 Yates, 1938, op. cit., p. 172.
    H.W. Fairbairn and G.M. Robson, 1942, "Breccia at Sudbury, Ontario," Journal of Geology, vol. 50, no. 1, p. 3.

42 Yates, 1938, op. cit., p. 169.

43 Cooke, 1946, op. cit., p. 62.

44 Yates, 1938, op. cit., p. 172.
    Fairbairn and Robson, 1942, loc. cit.

45 D.R. Lochhead, 1955, "The Falconbridge Ore Deposit, Canada," Economic Geology, vol. 50, no. 1, p. 45.

46 Knight, 1917, op. cit., pp. 132, 173, and 191.
    A.M. Clarke and P. Potapoff, 1959, "Geology of McKim Mine,"

Proceedings of the Geological Association of Canada, vol. 11, p. 73.

47 Yates, 1948, op. cit., p. 65.

48 Yates, 1938, op. cit., p. 171.

49 Yates, 1938, loc. cit.

50 Cowan, 1967, op. cit., p. 44.
    Naldrett and Kullerud, 1967, op. cit., p. 466.

51 Naldrett and Kullerud, 1967, op. cit., pp. 464-65.

52 Fairbairn and Robson, 1942, op. cit., p. 31.
    Cowan, 1967, loc. cit.

53 Cowan, 1967, loc. cit.
    Speers, 1957, op. cit., p. 505.

54 E.C. Speers, 1956, "The Age Relations and Origin of the
Common Sudbury Breccia," Unpublished Ph.D. Thesis, Queen's
University, in Naldrett and Kullerud, 1967, op. cit., p. 521.

55 Cowan, 1967, loc. cit.

56 Cowan, 1967, loc. cit.
    Speers, 1957, op. cit., p. 505.

57 A. Wandke and R. Hoffman, 1924, "A Study of the Sudbury
Ore Deposits," Economic Geology, vol. 19, p. 184.

58 Cowan, 1967, loc. cit.

59 Yates, 1948, op. cit., p. 603.

60 Knight, 1917, op. cit., p. 155.
    Cowan, 1967, op. cit., p. 51.

61 J.E. Thomson, 1957, "Geology of Falconbridge Township",
Department of Mines, Ontario, Annual Report, vol. 66, pt. 6, p. 25.
    Knight, 1917, loc. cit.
    H.F. Zurbrigg and Geological Staff, 1957, "The Frood-
Stobie Mine," in Structural Geology of Canadian Ore Deposits,
Congress Volume, Montreal, Canadian Institute of Mining and
Metallurgy, p. 347.

62 Lochhead, 1955, op. cit., p. 48.

CHAPTER III

EVIDENCE RELATIVE TO PROBLEMS OF THE SUDBURY AREA

Apparent Sequence of Events

The preceding, descriptive history of the Sudbury area is
summarized in Table 4 (see pages 15 and 16). As indicated,
five periods of intrusive activity are recognizable, each period
being characterized by an initial intrusion of acidic composition
followed in turn by one or more intrusions of basic composition.
The period of extrusive activity (2a & b) is also recognizable
as the equivalent of an acidic to basic period. As expressed by
Table 5 (page 19), the volcanic tuffs, composed of andesite,
bear a strong similarity of chemical composition to the combined
analyses of the micropegmatite and norite. All six periods of
igneous activity are therefore suggested as being representative
of relatively, continuous magmatic differentiation in a reservoir
at depth with periodical expulsions of differentiated magma
as indicated by Table 4.

Evidence of Genetic Relationships

The following evidence is presented as being indicative of
a genetic relationship among the various intrusives, and con-
sequently indicative of a common source of differentiated magma.
Characteristic intergrowths of potassium feldspar and quartz,
termed micrographic intergrowth, have been noted to occur in the
following rock types.

(1a) - grey granite [1]

(3a) - micropegmatite [2]

(3b) - norite [3]

(4a) - Creighton granite [4]

(4b) - quartz diorite [5]

   (4c) - an absence of micrographic intergrowth was noted
in the fine-grained, second intrusion of quartz
diorite [6]

(6a) - pegmatite - noted along the eastern range to be intruded
into brecciated rock adjacent to the irruptive and
subsequently intruded by nickel sulphides [7]

All of the above rock types are coarse-grained in texture,
consequently there is the probability that micrographic inter-
growth was not developed in the fine-grained rock types such
as andesitic tuff (2a & b), the aplites (5a) & (6a), and the
trap rock (5b). The remaining coarse-grained rock types of
quartz gabbro (1b) and porphyritic olivine diabase (1c) were
noted to respectively contain rounded masses of pegmatitic
quartz and feldspar, and white phenocrysts. [8]

Nature of the Sudbury Irruptive

Concepts of the Irruptive

Basically the irruptive has been considered as being in-
troduced into place as either:

(a) a single intrusion which differentiated in place into the
component parts of micropegmatite and norite, as inter-
preted by such men as Walker (1897), Bell (1890), Coleman,
(1903), Collins (1934), and Hawley (1962),

(b) or as two separate intrusions, with a differentiated fraction
of norite intruded initially and followed by a differentiated
fraction of micropegmatite, with this interpretation proposed
by such men as Harker (1916), Knight (1923), Phemister (1925),
Stevenson (1963), and Naldrett and Kullerud (1967).

Suggested Third Concept of the Irruptive

A third concept of the emplacement of the irruptive is
suggested as being more feasible than either of the above con-
cepts. At depth, a magma of basic composition may be considered
as having differentiated into a basic fraction of noritic com-
position with an overlying, residual, acidic fraction of micro-
pegmatitic composition. If a portion of such differentiated
magma were expelled from the reservoir, the overlying micro-
pegmatitic fraction would be the first to be emplaced into the
overlying country rock, with the noritic fraction emplaced either
with this acidic fraction or closely following it. Prior to
consolidation, both fractions could have undergone further
differentiation in place.
As may be noted, this third concept is a modification of the
'single intrusion' and the 'two separate intrusions' concepts,
with emplacement of the irruptive considered as either a
relatively continuous, single intrusion or as two intrusions
closely related in time, such fractions having been differentiated
primarily in the magma reservoir and to a relatively minor degree
following emplacement.

Evidence of an Initial Emplacement of Micropegmatite

As the 'two separate intrusions' concept envisions the
noritic fraction as having been initially emplaced, the
following evidence is presented as being indicative that the
micropegmatitic fraction was initially emplaced.
(a) As shown by Figure 8, the country rock presently exposed
along the northern and eastern ranges of the irruptive is com-
posed of granite and granite gneiss, with quartzite exposed
south of the irruptive's southern range. Stevenson (1963) has
noted the micropegmatite to be intrusive into quartzite breccia
and the overlying volcanic tuff, as well as containing inclusions
of coarse-grained "old granite". [9]   Occasional fragments of

quartzite have also been noted within both the norite and the
hybrid zone, thereby suggesting that such rock-types were also
intrusive into the country rock but to a probable lesser degree
than the intrusion of micropegmatite. [10]

(b) Such intrusive relationships are diagrammatically expressed
by the suggested, hypothetical cross-section of the irruptive
(Figure 6). An initial intrusion of norite would be improbable
if such a configuration were to be accepted for the nature of
the irruptive at depth.

(c) As noted by Table 4, sequences of acidic to basic intrusions
occurred both prior to and after the intrusion of the irruptive.
A reversal of such an acidic to basic sequence for just the
irruptive would appear to be quite doubtful.

(d) Magmatic differentiation implies a gravitational segregation
of the heavier and earliest formed crystals from the lighter
and later formed crystals. It is consequently difficult to
visualize a differentiated fraction of norite with an average
specific gravity of 2.8175 as having been intruded prior to a
differentiated fraction of micropegmatite with an average
specific gravity of 2.708. [11]

(e) Collins (1934) largely discounted the possibility of sig-
nificant differentiation in place, as inferred by the 'single
intrusion' concept, by his observation that "there is not a
regular change in acidity and specific gravity across the
irruptive." [12]   Both the micropegmatite and norite were found
to have characteristic chemical compositions, suggestive of
significant differentiation prior to intrusion rather than
following intrusion. [13]

Evidence of Partial Differentiation in Place

Narrow zones of varying texture and composition, noted
along the upper and lower contacts of both the micropegmatite
and the norite, are suggestive of a partial differentiation in

place following the intrusion of the irruptive.

An upper, contact phase of the usual, coarse-grained
micropegmatite has been recognized by Stevenson (1963) as a
medium to fine-grained rock over a surface-distance of 500 feet. [14]
Tongues of this rock-type, termed pepper-and-salt micropegmatite,
were noted as intrusive into the overlying quartzite breccia
and the volcanic tuff for distances of hundreds of feet.
One such tongue was noted by Collins (1934) to have a specific
gravity of 2.697 as compared with an average of 2.708 for the
usual coarse-grained micropegmatite. [15]

The hybrid zone of mixed acidic and basic composition,
exposed over a surface distance of 250 to 800 feet (Figures 6
and 8), may be representative of an intermingling of the fractions
of micropegmatite and norite during intrusion. As indicated by
the work of Collins (1934), this zone is characterized by a
composition high in FeO and TiO_2, being representative of the
heavy mineral ilmenite. [16] A gravitational differentiation of
ilmenite from the overlying micropegmatite appears to be probable.
A number of small concentrations of ilmenite around the border
of the norite are also suggestive of a partial differentiation
of ilmenite from the norite.

An upper, pegmatitic phase of the norite has been
recognized by Yates (1938) as underlying the hybrid zone almost
completely around its periphery, with an exposed width of a few
feet to several hundred feet. [17] This phase could be considered
as a partial differentiation of the norite in place as the result
of an upward migration of volatile solutions with a consequent
recrystallization of the original constituents of augite and
hypersthene to the less basic minerals of hornblende, biotite
and chlorite. [18]

Evidence of a possible differentiation of the norite at
depth has been indicated by inclusions of ultrabasic composition
contained within the later intrusion of quartz diorite (4c)(see page 23).[19]

Ultrabasic inclusions have been also noted within zones of massive
sulphide mineralization. [20] Such inclusions are inferred as
having been fractured by the intrusion of quartz diorite (4c)
and possibly by the intrusion of massive sulphides (6c) from
a differentiated zone believed to underlie the norite of the
irruptive (Figure 6). If such intrusions were injected along the
same system of tension fractures as inferred by their spacial
relationships, a possibility also exists that ultrabasic
inclusions might have been also fractured from this zone by the
intrusions of granite (4a) and quartz diorite (4b), and carried
upwards in suspension.

Relative Times and Degrees of Brecciation

A review of the published reports relative to the Sudbury
area has indicated that the various degrees of brecciation:
(a) were closely associated with major tension fractures or
fissures, presently exposed as brecciated bands roughly parallel
to the periphery of the irruptive or as bands radiating outwards
from the irruptive (see Figure 8);
(b) were of major intensity prior to and during the extrusion
of volcanic tuff (2a & b);
(c) were of moderate intensity prior to the intrusion of nickel
sulphide mineralization (5c) and (6c);
(d) and were of minor intensity in association with the outer
margins of the forceful intrusions of micropegmatite (3a),
norite (3b), granite (4a), quartz diorite (4b) & (4c) and
trap rock (5b).
A pre-irruptive age for the period of major brecciation is
indicated at locations where the norite of the irruptive has been
intruded across breccia zones. [21] The nature of this breccia
is well illustrated by the observation of Yates (1948) that the
breccia near the Frood mine (southern range) carries fragments
"of all sizes from microscopic to as great as 3,000 feet in
length and 1,000 feet in width." [22]

Structural Shape of the Irruptive at Depth

The irruptive has been variously described as the surface expression of:

(a) a folded, differentiated sill, (Walker, 1897) (Coleman, 1905)

(b) an intrusion around a downfaulted block, (Knight, 1917)

(c) a ring-dyke complex, (Phemister, 1925)

(d) an intrusion into a pre-existing syncline, (Yates, 1948)

(e) an intrusion as a funnel-shaped body, (Wilson, 1956)

(f) a ring-dyke complex which converges rather than diverges
     at depth, (Thomson, 1956)

(g) an intrusion into a collapse caldera, (Speers, 1957)

(h) and an extrusive lopolith in an "astrobleme". (Dietz, 1962)

The hypothetical view of the irruptive at depth as suggested by
Figure 6 is a diagrammatic interpretation suggestive of the
descriptive hypotheses of Knight (1917) (b), and Thomson (1956)
(f). Thomson felt obliged to consider a pre-existing basin as
an explanation for the inward dipping nature of the volcanic
tuff formations, however, such a feature could also be explained
as an accumulation of breccia adjacent to volcanic fissures, a
gradual subsidence of a fault block, and a gradually diminishing
fall-out of volcanic tuff toward the center of the irruptive,
as suggested by Figures 5 and 6. A study by Wilson (1956) of
layered intrusions suggested that 5 to 10 per cent of a basaltic
magma could be differentiated to granitic material. [23]
The amount of micropegmatite shown by Figure 6 is in accord
with such an expected range of differentiation. As also shown,
the attitude of the norite conforms with the observation made
by Souch, Podalsky et al and noted by Naldrett and Kullerud (1967)
that "the dip of the primary foliation in the feldspars and
pyroxenes is flatter than the dip of the outer contact of the
intrusion". [24]

Genesis of the Ore Deposits

The numerous hypotheses proposed to explain the structure
of the irruptive at depth have their counterpart in the number
of hypotheses proposed as explanations for the origin of the
Sudbury nickel ores, such as:

(a) fissure-fillings by solutions, (Collins, 1888)

(b) segregation of sulphides from the noritic magma as
immiscible droplets with a later injection into
underlying fractures, (Bell, 1890) (Walker, 1897)
(Coleman, 1905) (Collins, 1934) (Hawley, 1962)
and others

(c) hydrothermal replacements of the country rock and
intrusives, (Knight, 1917) (Phemister, 1925) (Burrows
and Rickaby, 1934) and others

(d) introduced in suspension with the latest intrusion of
quartz diorite, (Naldrett and Kullerud, 1967)

(e) differentiation at depth with a later emplacement into the
overlying country rock and intrusives as injections of
sulphide magma. (Howe, 1914) (Bateman, 1917)

As suggested on page 4, all of these hypotheses might be viewed
in the perspective of a single hypothesis, namely magmatic
differentiation in a magma reservoir at depth. Yates (1948)
indicated that a lengthy and complex period of igneous activity
preceded the emplacement of the ore deposits.[25] Such in-
ferred complexity of igneous activity has been shown by Table 4
to consist of an orderly number of periods each being characterized
by an acidic to basic sequence of intrusions.

The assumption may be made that nickel sulphides were
originally contained within a magma of basic composition at
such time as it had been emplaced into a reservoir at some
undetermined depth below the present site of the irruptive.
With a slow rate of cooling, the magma differentiated into
fractions of acidic to basic composition which were periodically

expelled under various degrees of accumulated pressure.
Assuming that the contained sulphides had also undergone
gravitational differentiation during this time, a concentration
of sulphides could be expected within the lower portion of the
basic fraction or to lie immediately below it. At such times
as periodic explusions of differentiated magma occurred, the
concentrations of sulphides would be expelled with a basic
fraction or as closely following fraction of concentrated
sulphide magma. As indicated by Table 4, (pages 15 and 16)
this sequence is indicated by the events (3b), (4c), (5c) and
(6c). Partial evidence of such concentration may be inferred
from Table 7.

Table 7
Relative Concentrations of Nickel, Copper and Sulphu

| | mean values in ppm | | |
	Ni	Cu	ఠ
micropegmatite	20	28	475
upper norite	35	40	950
norite (northern range)	60	55	950
norite (southern range)	75	50	1,100
discontinuous marginal facies	3,000	2,700	18,000

Source: Souch et al, 1966, p. 801.

At such time as the intrusion of the norite, the nickel content
of this portion of differentiated magma contained a sulphide
concentration of 0.0035 to 0.007 per cent. The later intrusion
of quartz diorite, (4c), having undergone further differentiation
at depth, contained approximately 0.3 per cent nickel, being 0.1
per cent higher in nickel content than the average peridotite of
ultrabasic content (see Table 1, page 3). Evidence is not
available, however, it is suggested that the sulphides introduced
during event (5c) were of a greater concentration than the contained

sulphides emplaced during event 4c. At such time as event 6c, the sulphides had been concentrated to approximately 4 to 10 per cent nickel content and emplaced as massive sulphide deposits. [26]

By the apparent sequence of intrusions of late mineralization at the Marbridge mines in the Malartic district of Quebec (see page 60), it may be inferred that the arsenides of nickel and the monosulphide of nickel, millerite, were emplaced in the Sudbury area following the intrusion of massive sulphides but prior to the intrusion of the sulphide minerals sphalerite, galena and marcasite (see page 30).

FOOTNOTES FOR CHAPTER III

1 G.P. Mitchell and A.D. Mutch, 1957, "Hardy Mine" in Structural
Geology of Canadian Ore Deposits, Congress Volume, vol 2,
Montreal, Canadian Institute of Mining and Metallurgy, p. 352.

2 A.J. Naldrett and G. Kullerud, 1967, "A Study of the
Strathcona Mine and Its Bearing on the Origin of the Nickel-
Copper Ores of the Sudbury District, Ontario," Journal of Petrology,
vol. 8, pt. 3, p. 519.
    J S. Stevenson, 1963, "The Upper Contact Phase of the
Sudbury Micropegmatite," Canadian Mineralogist, vol. 7, p. 413.

3 T.C. Phemister, 1925, "Igneous Rocks of Sudbury and their
Relation to the Ore Deposits," Department of Mines, Ontario,
vol. 34, pt. 8, 1926, pp. 6, 10 and 19.
    Naldrett and Kullerud, 1967, loc. cit.

4 E. Howe, 1914, "Petrographical Notes on the Sudbury Nickel
Deposits," Economic Geology, vol. 9, no. 6, pp. 518-19.

5 A.G. Burrows and H.C. Rickaby, 1934, "Sudbury Nickel Field
Restudied," Department of Mines, Ontario, vol. 43, pt. 2,
1935, p. 27.
    A.B. Yates, 1938, "The Sudbury Intrusive," Transactions
of the Royal Society of Canada, vol. 32, sect. 4, p. 163.
    J.C. Cowan, 1967, "Geology of the Strathcona Ore Deposit,"
Canadian Mining and Metallurgical Bulletin, vol. 1, no. 669,
1968, p. 43.

6 Naldrett and Kullerud, 1967, op. cit., p. 492.

7 H.C. Cooke, 1946, Problems of Sudbury Geology,
Geological Survey, Canada, bull. no. 3, p. 61.

8 Ibid., p. 58.

9 Stevenson, 1963, loc. cit.

10 W.H. Collins, 1934, "Life History of the Sudbury Nickel
Irruptive," Transactions of the Royal Society of Canada, vol. 28,
sect. 4, pp. 150-51.

11 Yates, 1938, op. cit., p. 153.

12 Collins, 1934, op. cit., pp. 142-48.

13 Ibid., p. 149.

14   Stevenson, 1963, op. cit., p. 415.

15   Collins, 1934, op. cit., p. 175.

16   Collins, 1934, op. cit., pp. 143, 145, and 148.

17   Yates, 1938, op. cit., p. 157.

18   Yates, 1938, loc. cit.

19   Naldrett and Kullerud, 1967, op. cit., p. 493.

20   B.E. Souch and Members of the Geological Staff of the
International Nickel Co. of Canada Ltd., 1966, "The Sulfide
Ores of Sudbury: Their Particular Relation to a Distinctive
Inclusion-Bearing Faces of the "Nickel Irruptive", Abstract,
Economic Geology, vol. 61, pt. 1, p. 801.

21   E.C. Speers, 1957, "The Age Relation and Origin of Common
Sudbury Breccia," Journal of Geology, vol. 65, p. 508.

22   A.B. Yates, 1948, "Properties of the International
Nickel Company of Canada," in Structural Geology of Canadian
Ore Deposits, Jubilee Volume, Montreal, Canadian Institute of
Mining and Metallurgy, p. 612.

23   H.D.B. Wilson, 1956, "Structure of Lopoliths," Bulletin
of the Geological Society of America, vol. 67, pt. 1, p. 299.

24   B.E. Souch, T. Podalsky and Geological Staff of the
International Nickel Co. of Canada Ltd., The Sulfide
Ores of Sudbury: Their Particular Relation to a Distinctive
Inclusion-Bearing Facies of the Nickel Irruptive, Unpublished
Study, in Naldrett and Kullerud, 1967, op. cit., p. 492.

25   Yates, 1948, op. cit., p. 603.

26   Naldrett and Kullerud, 1967, op. cit., p. 494.

CHAPTER IV

SEQUENCES OF EVENTS IN OTHER NICKEL RESOURCE-AREAS

The areas of Lynn Lake, Moak Lake-Setting Lake, Bird River,
Werner Lake-Gordon Lake, Shebandowan and Marbridge (Figure 3) have
been reviewed with the object of determining the apparent sequences
of events. Relative to the Sudbury area, comparatively little
information has been published concerning these areas. Assuming
that a somewhat progressive sequence of acidic to basic intrusive
events might be indicated in a number of these areas, the origin
of the concentrated nickel deposits might be attributed to a
common process of magmatic differentiation at depth. The apparent
sequences of events have been summarized in Table 8 (see page 62).

The Lynn Lake Area

The first evidence of igneous activity in the Lynn Lake
area has been noted as the extrusion of minor rhyolite and
trachyte flows, followed by major extrusions of andesitic tuff
and breccia. [1] Minor periods of sedimentation intervened between
the explusions of the andesite and continued for a following,
lengthy period.

Regional folding compressed the volcanic and sedimentary
formations into a tightly folded, synclinal structure accompanied
by an intrusion of granite roughly concordant with the east-west
trend of the folded structure. A similar age for both the folding
and the emplacement of the granite is evidenced by zones of
crushed granite. [2]

The granite was in turn followed by the intrusion of
plug-like bodies of basic composition. As shown by Figure 12,
the ore deposits of the area are associated with two of these
plugs, which have been termed the "A" plug and the "EL" plug.
The rock-types of which these plugs are composed have been
described by various terms, however, the phases of diorite,
gabbro and norite have been recognized and suggested as being
the result of differentiation in place. Interrelationships
between these phases are not apparent in Figures 13 and 14
due to the grouping of such rock types under the inclusive
term of diorite.

Compression from the west is considered to have been
responsible for the formation of major thrust faults aligned in
a north-south direction. Associated minor faults and tension
fractures cut the plugs in northeast and northwest directions
and were the apparent paths along which irregular masses of
peridotite were intruded. Zones of brecciation were formed
at right angles to the major north-south faults. Such
brecciated and faulted zones were apparently pathways for hydro-
thermal solutions which altered parts of the diorite, gabbro
and norite to amphibolite, characterized by actinolitic
hornblende.[3] Most of the previously intruded peridotite was
altered to serpentine and talc. Wide zones of this alteration
were noted as both adjacent to and also distant from the ore
zones.[4] Consequently, such alteration was not an intimately
associated product of ore-bearing solutions.

In turn, minor acidic dykes of granite, pegmatite and
feldspar porphyry were intruded. Following the acidic dykes,
unaltered dykes of quartz hornblende diorite are believed to
have been emplaced, however, cross-cutting relationships had
not been confirmed at the mines by 1960.[5] To the east of
the Lynn Lake area, Allen (1950) reported the occurrence of basic
dykes cutting acidic dykes, with both dykes cut in turn by
quartz veins.[6]

LEGEND

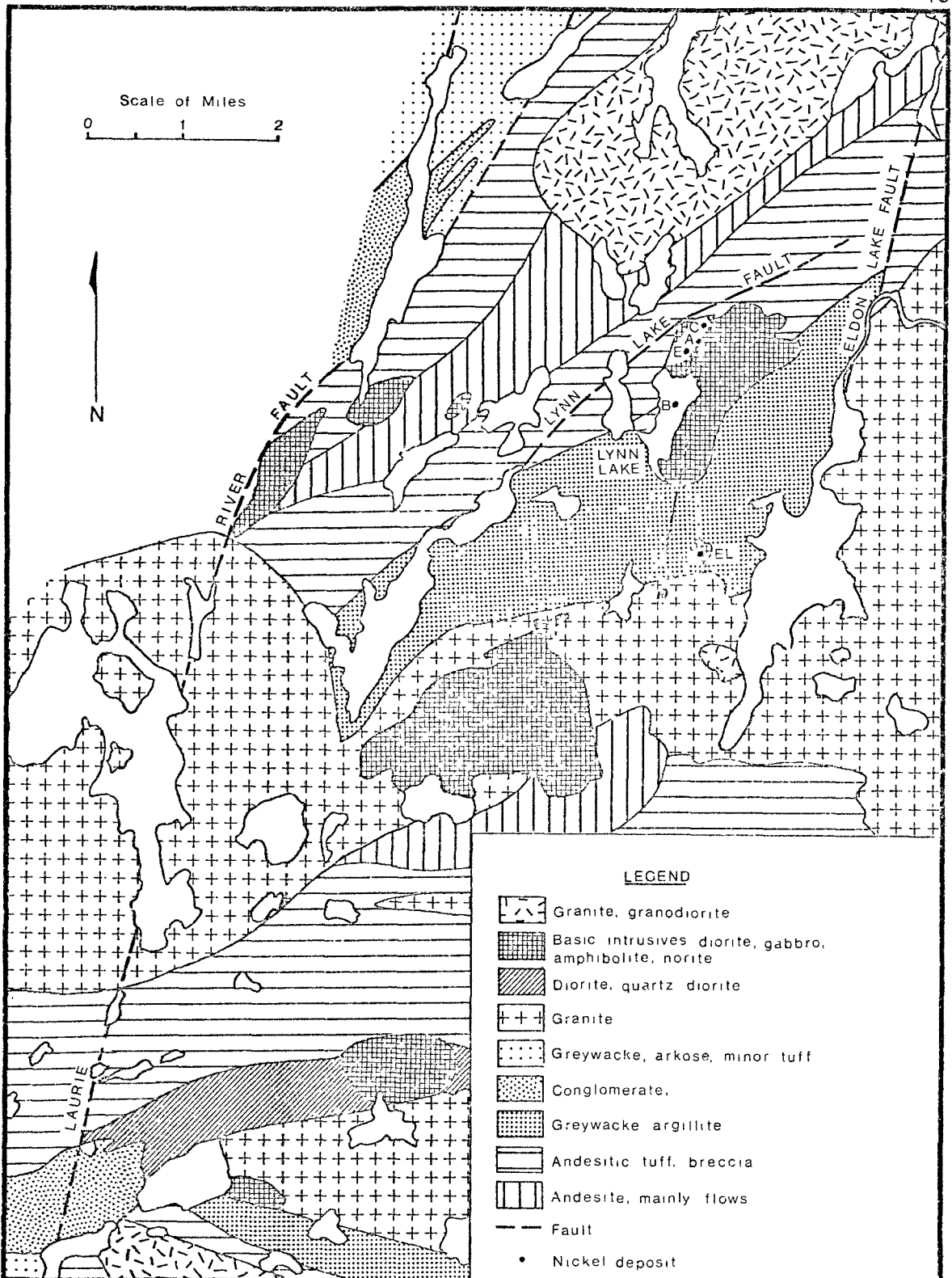|	
Granite, granodiorite
Basic intrusives diorite, gabbro, amphibolite, norite
Diorite, quartz diorite
Granite
Greywacke, arkose, minor tuff
Conglomerate,
Greywacke argillite
Andesitic tuff. breccia
Andesite, mainly flows
Fault
Nickel deposit

FIGURE 12. Geological map of the Lynn Lake area, Manitoba.
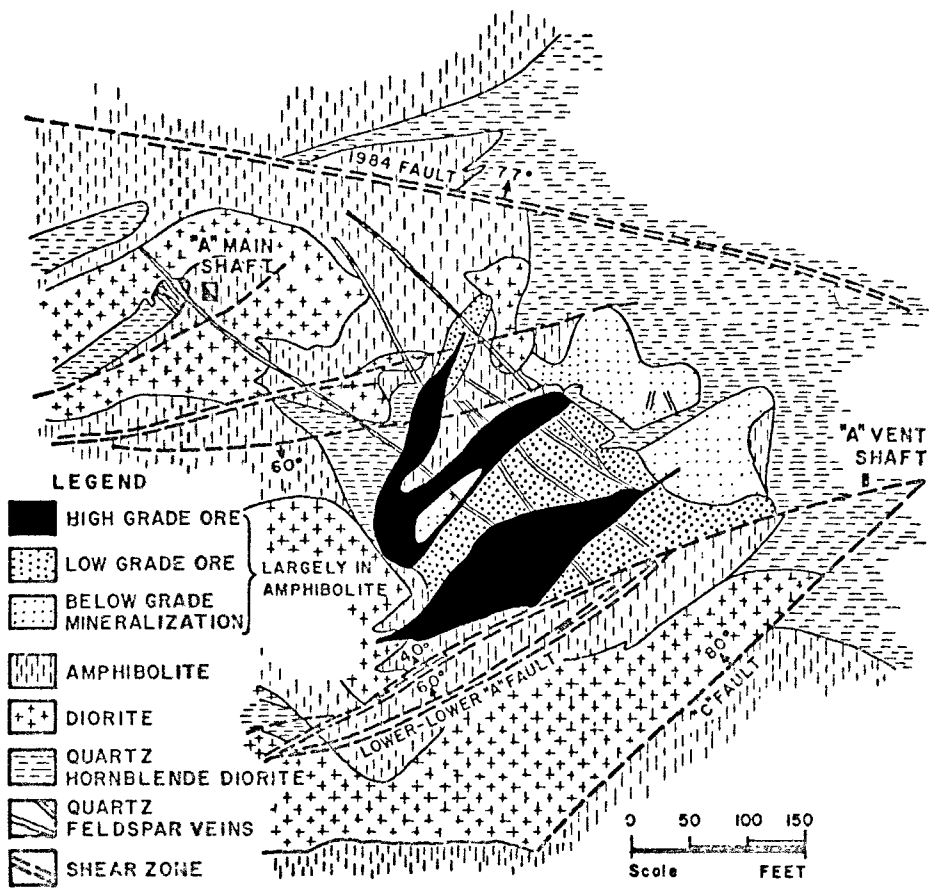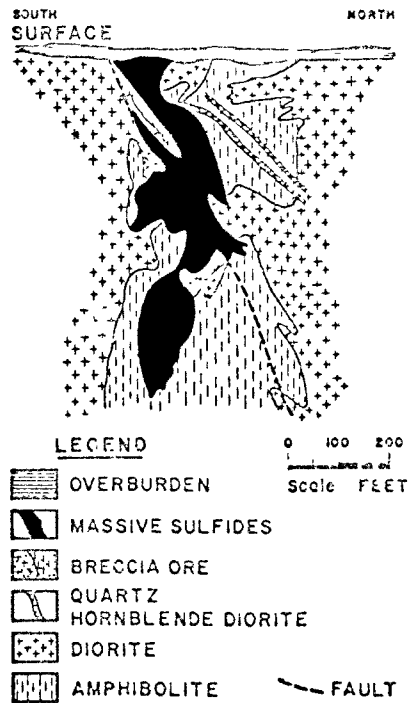(modified after Ruttan, 1955)

FIGURE 13. Geological plan of the 'A' orebody at the 12th level, Lynn Lake mine. (from The Winning of Nickel, 1967)

FIGURE 14. Cross section of the 'EL' orebody, Lynn Lake area, Manitoba. (from The Winning of Nickel, 1967)

A period of brecciation, shearing and minor faulting
fractured the previously intruded rock-types and provided
avenues of access for sulphide mineralization. As observed
by Ruttan (1955):

> The grade of the ore is directly proportional to the
> intensity of the brecciation, with the highest grade
> material originating at or near one of the faults, and
> extending toward the next fault. [7]

Within the massive sulphide deposit of the "EL" mine, rounded,
unmineralized inclusions were noted as being composed of diorite,
norite, amphibolite and quartz hornblende diorite. [8] The rounding
of such fragments might be viewed as the result of localized
intensive brecciation with a tumbling of such fragments together,
and followed by a forceful intrusion of concentrated sulphide
mineralization.

The Moak Lake-Setting Lake Area

The first apparent event of igneous activity to take
place in the Moak Lake-Setting Lake area was the extrusion of
andesite and/or basalt. [9] As these volcanic rocks are inter-
bedded with considerable thicknesses of sedimentary formations,
lengthy periods of sedimentation are implied.

As shown by Figure 15, the presently exposed configurations
of the sedimentary and volcanic formations are indicative of a
highly folded belt approximately eighty miles in length.
Granite was apparently intruded during the period of folding as
inferred by evidence of post-crystalline brecciation and shearing. [10]
Patterson (1963) suggested that the foliated, basic sills
reported near Mystery Lake may have been intruded close to the
end of this orogenic period. [11]

As illustrated by Figure 15, rounded to oval-shaped
bodies of granite have been mapped northeast of the Thompson
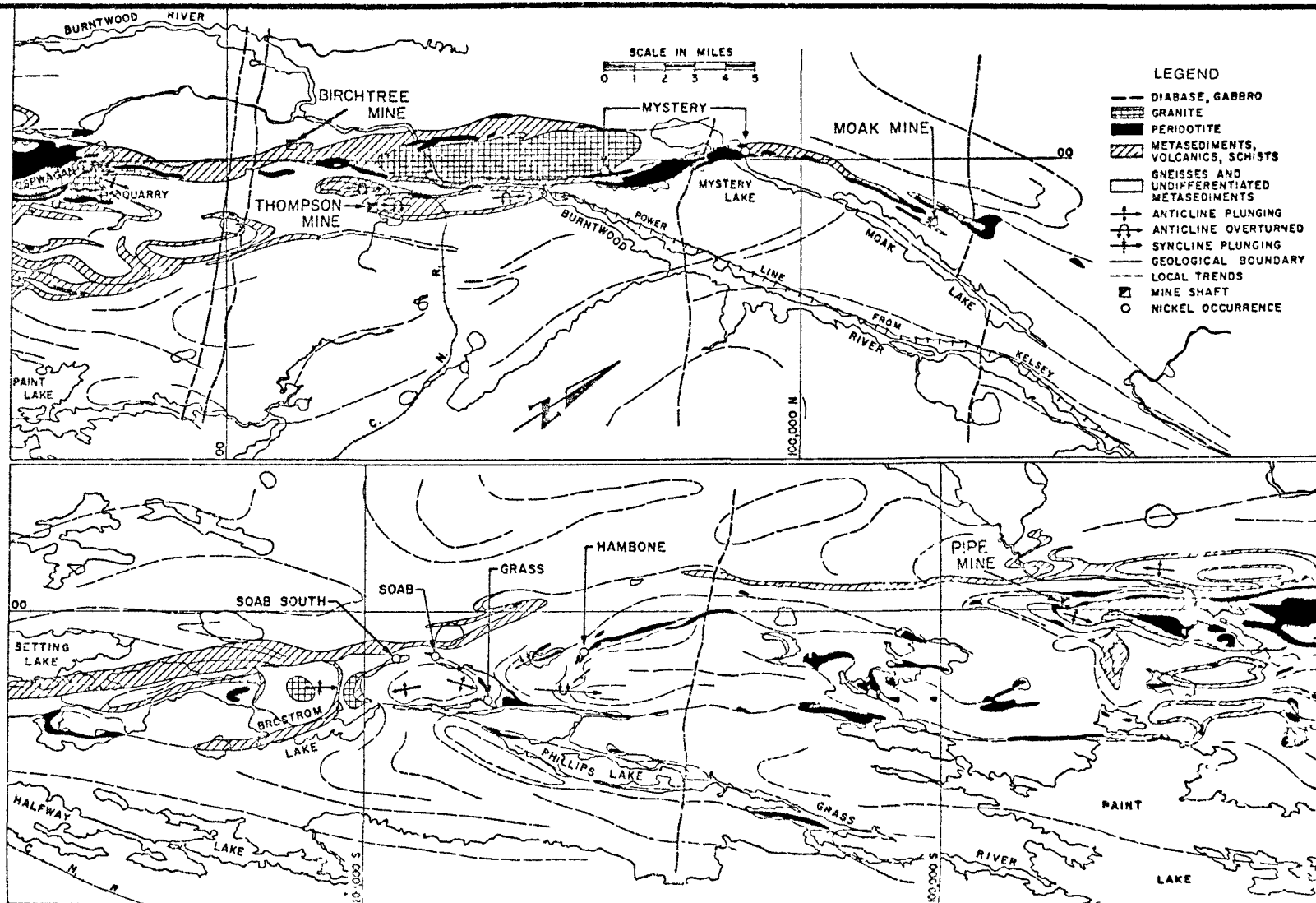mine, east of the Pipe Lake mine and southwest of the Soab mines.

FIGURE 15. Geological map of the Moak Lake-Setting Lake area, Manitoba. (from The Winning of Nickel,1967)

Irregular contacts of these bodies with the surrounding country
rocks suggest that the granite was intruded following the period
of orogeny, however, cross-cutting relationships with the later
intrusions of peridotite have not been established. [12]

Throughout the eighty-mile long belt, elongate bodies of
ultrabasic composition have been intruded roughly parallel
to the northeast trend of the folded country rock and in some
locations are closely associated with extensive, regional faults.
These formations have been recognized as being composed mainly
of peridotite with minor dunite and pyroxenite. [13] At the
Thompson mine, a small mass of peridotite was found to be cut
by pegmatite which was in turn cut by massive nickel sulphides.[14]
Mineralized, quartz vein fillings were also noted at the Moak
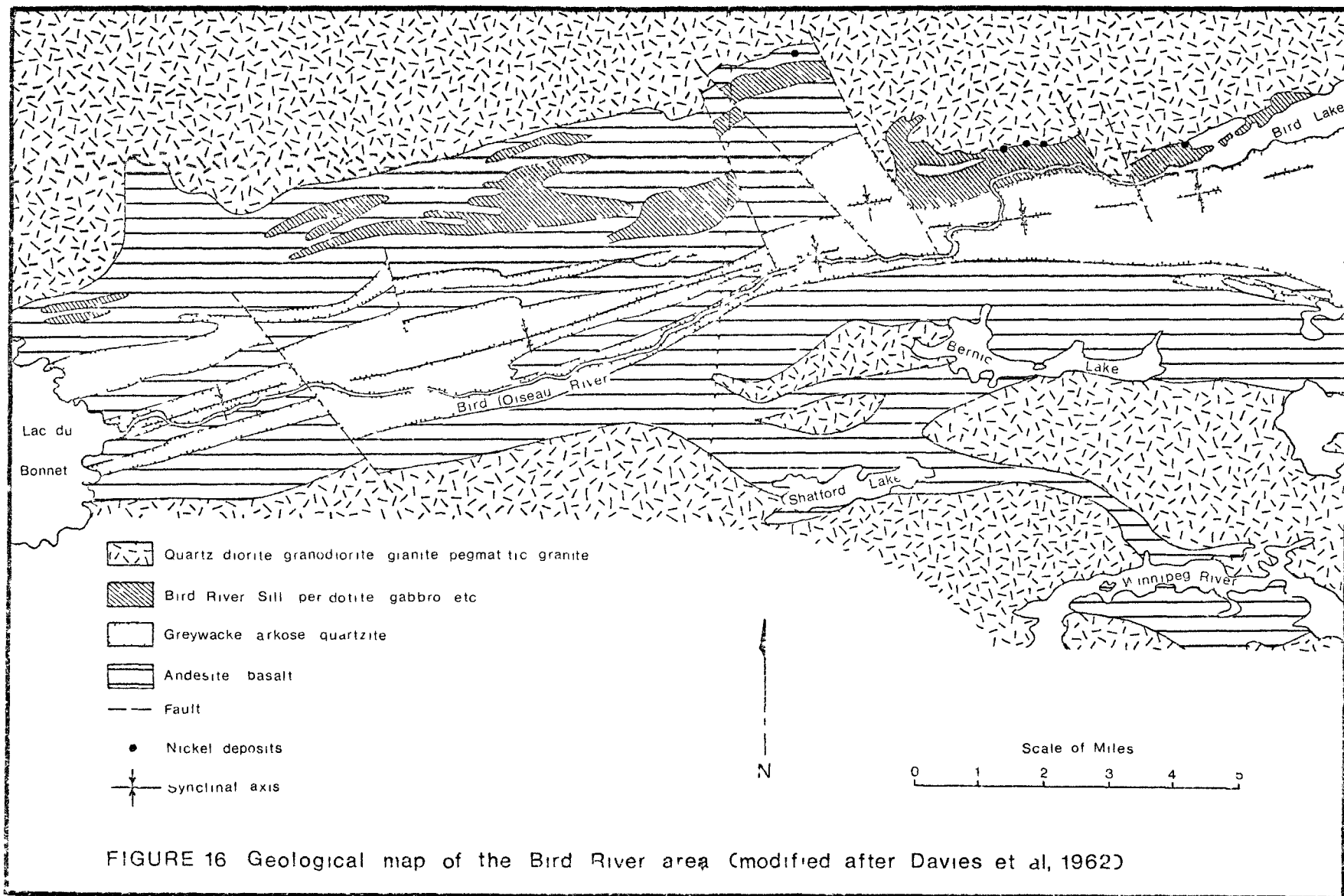mine within a peridotite sill. [15]

The majority of the ultrabasic rocks in the area have been
altered to serpentine. [16] At one of the mines in the area, the
writer noted the peridotite adjacent to the ore zone to be
intensively altered to a talc-like composition, with fresh-appear-
ing, rounded inclusions of peridotite present in the midst of
massive sulphide mineralization. Such an occurrence indicates
that the peridotite was locally altered to a talc-like comp-
osition prior to the emplacement of the massive sulphides and
not as an intimate product of the intrusion of the sulphide
mineralization.

A few of the peridotite bodies, such as the Moak Lake
sill, have been partially sheared and brecciated with zones of
disseminated sulphides and sulphide stringers. Other deposits,
such as the Thompson mine, occur as breccia sulphide and
massive sulphide zones essentially concordant with the regional
structure of the metamorphosed sedimentary and volcanic formations.

The Bird River Area

The oldest rocks exposed in the area are represented by
lava flows of andesite and basalt . As shown by Figure 16,
these lavas flank a later formation of sedimentary rocks which
contain interbedded volcanic tuff. A period of major folding
and faulting compressed these formations into a synclinal
structure with steeply dipping beds. As noted by Davies (1955),
granite was intruded into the southern limb of the syncline,
however, he considered the granite along the northern limb to
be intrusive into the Bird River sill, an intrusion composed
primarily of peridotite and gabbro. [17] In an earlier study,
Cooke (1921) considered this basic sill to have been intruded
into the granite. [18] Consequently, a younger or older age
for the granite relative to the Bird River sill appears to be
quite indecisive in this area.

As shown by Figure 16, the Bird River sill is exposed as
a number of segments displaced by late faults. The sill
dips steeply to the south and is composed of a lower band of
peridotite with overlying phases of pyroxenite and gabbro of
successively less basic composition. [19] Such a compositional
succession is suggestive of differentiation primarily in place.
In various locations, gabbro was noted to underlie the
peridotite and to be also contained within it. Such bands of
gabbro were inferred by Davies (1955) to represent a separate and
later intrusion than the Bird River sill. [20] Minor intrusions of
felsite, quartz and carbonate followed the basic intrusions
and were in turn fractured and mineralized by cross-cutting
sulphide stringers. [21] Lenses of massive sulphides were
noted primarily along contacts between the peridotite and the
granite, and also to be intrusive into these rock-types. The
Bird River sill was later segmented and displaced by cross-
faults with a following intrusion of large scale masses of
granite.

Quartz diorite granodiorite granite pegmatitic granite

Bird River Sill peridotite gabbro etc

Greywacke arkose quartzite

Andesite basalt

— — Fault

● Nickel deposits

Synclinal axis

Scale of Miles

0   1   2   3   4   5

N

FIGURE 16 Geological map of the Bird River area (modified after Davies et al, 1962)

The Werner Lake-Gordon Lake Area

As an extension of the Bird River area, approximately twenty to thirty miles directly east, the Werner Lake-Gordon Lake area shares evidence of a similar sequence of events (Figure 17). The question of whether granite might have been intruded prior to the emplacement of the Bird River sill is answered by the presence of elongate intrusions of granite relatively concordant with the regionally folded and metamorphosed sedimentary formations. This granite was subsequently cut by major faults along which elongate plugs and lenses of peridotite and pyroxenite were intruded. A medium-grained amphibolite was noted by Carlson (1957) to enclose such plugs and lenses, with the suggested possibility that the amphibolite might represent a possible later intrusive which had been completely altered by hydrothermal solutions. [22] Evidence of extensive hydrothermal activity was also indicated by a partial serpentinization of the peridotite and pyroxenite with a possible, complete alteration of such ultrabasic rocks to hornblendite in some locations. [23] All of the basic and ultrabasic rock types were noted to be cut by later granite-pegmatites. [24] A period of minor faulting and brecciation followed the intrusion of the granitic dykes and provided access for sulphide mineralization to form deposits of massive sulphides, breccia sulphides, sulphide stringers and disseminated sulphides. [25]

The Shebandowan Area

As indicated by Figure 18, extrusive activity is represented in the area by initial, acidic flows of rhyolite and trachyte, followed by basic flows of basalt, andesite, diorite and dacite with interbedded volcanic agglomerate. [26] Following a period of erosion, sedimentation, folding and faulting, lens-shaped bodies of peridotite were emplaced parallel with the regional foliation. [27] These bodies were subsequently largely altered to
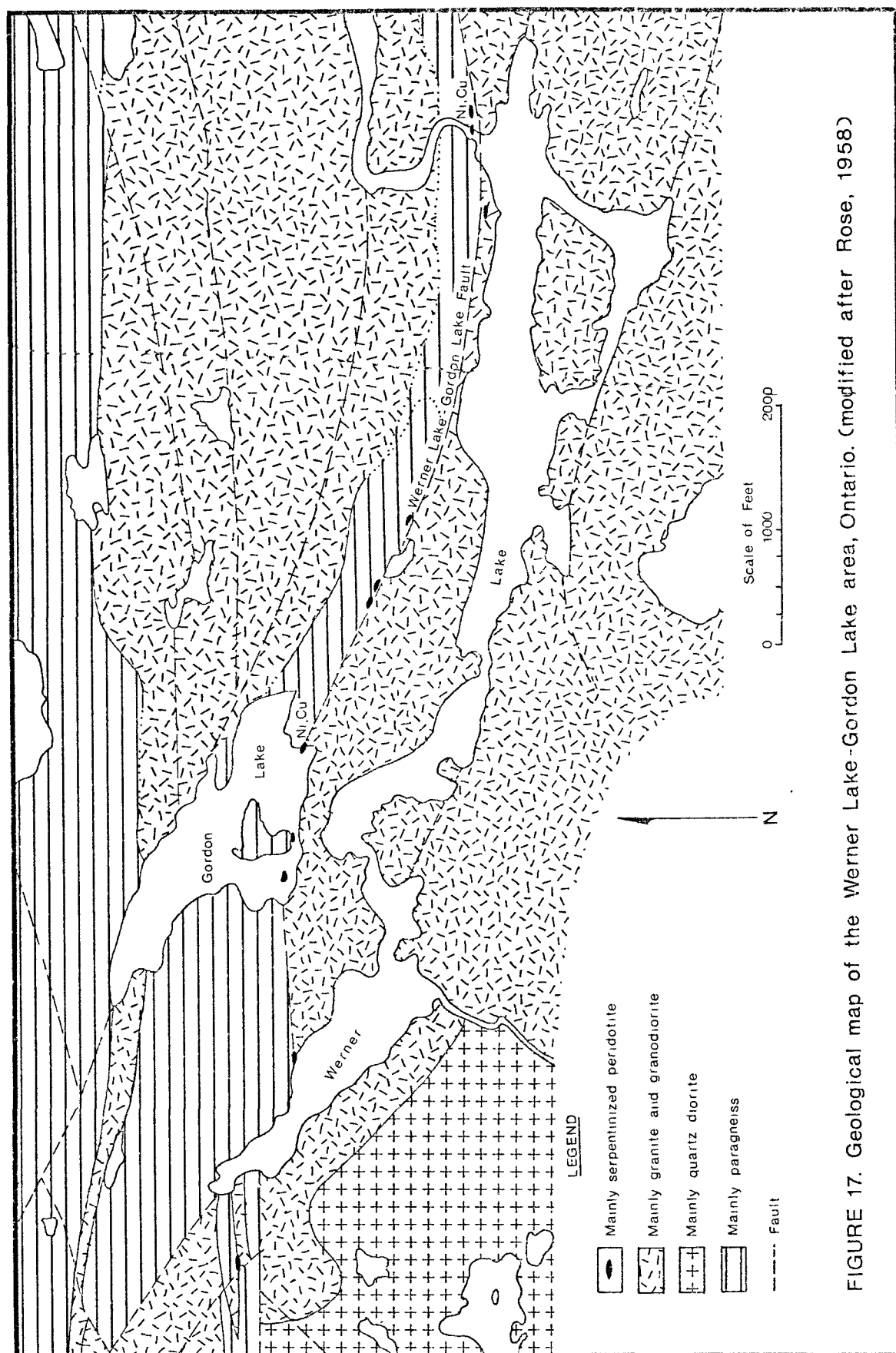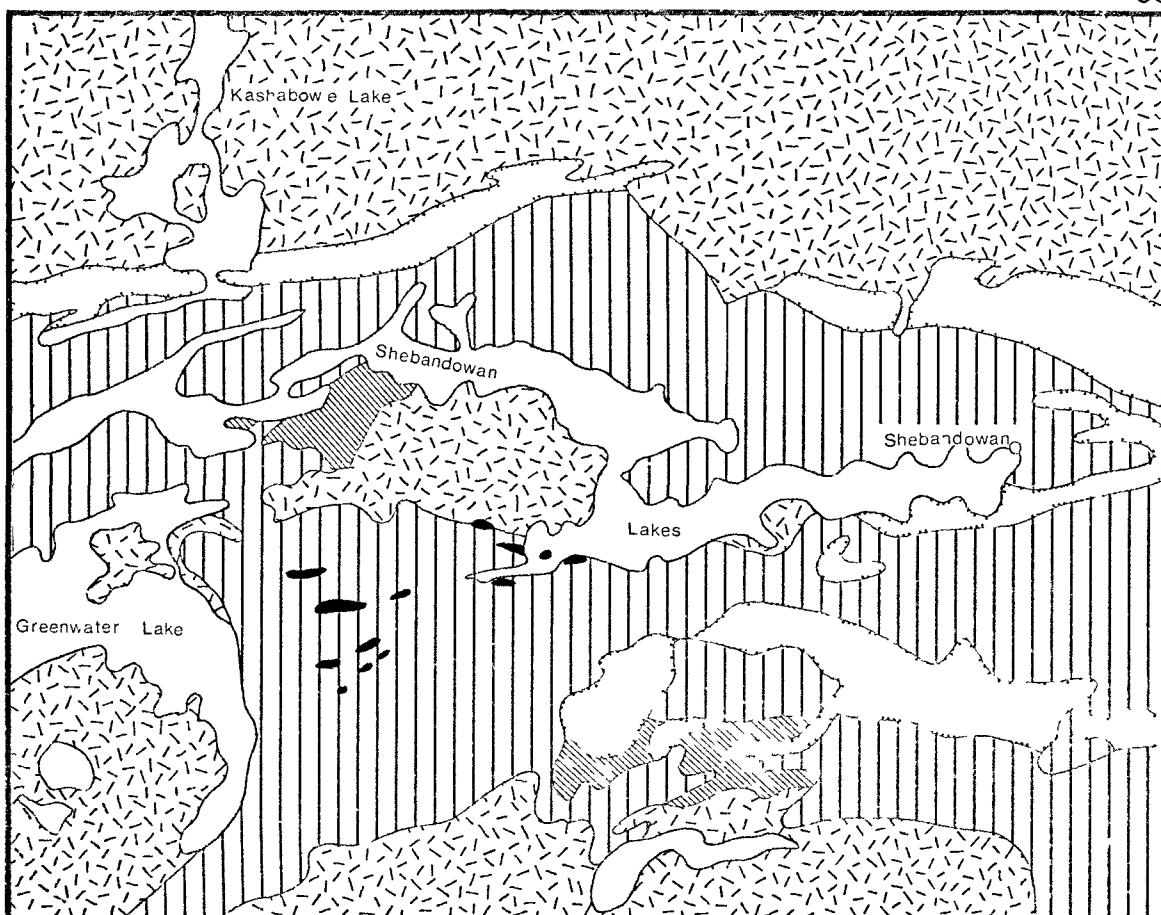
FIGURE 17. Geological map of the Werner Lake-Gordon Lake area, Ontario. (modified after Rose, 1958)

LEGEND

Manly serpentinized peridotite

Manly granite and granodiorite

Manly quartz diorite

Manly paragneiss

Fault

Scale of Feet

0   1000   2000

N

Gordon Lake

Werner

Lake

Ni,Cu

Ni,Cu

Werner Lake-Gordon Lake Fault

LEGEND

Granite quartz diorite

Gabbro locally anorthositic

Peridotite hornbendite gabbro

Sandstone conglomerate pyroclastics andesite

Paragneiss

Basalt minor pyroclastics

N

Scale of Miles

0   5

FIGURE 18 Geological map of the Shebandowan area, Ontario (modified after Watkinson and Irvine, 1964)

serpentine. Bodies of gabbro were noted to occur both adjacent
to the peridotite and also at some distance away, being indicative
of a later intrusion of gabbro. [28] The peridotite was in turn
cut by dykes of porphyritic quartz and feldspar which were
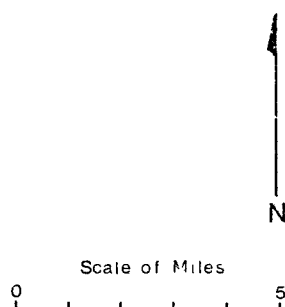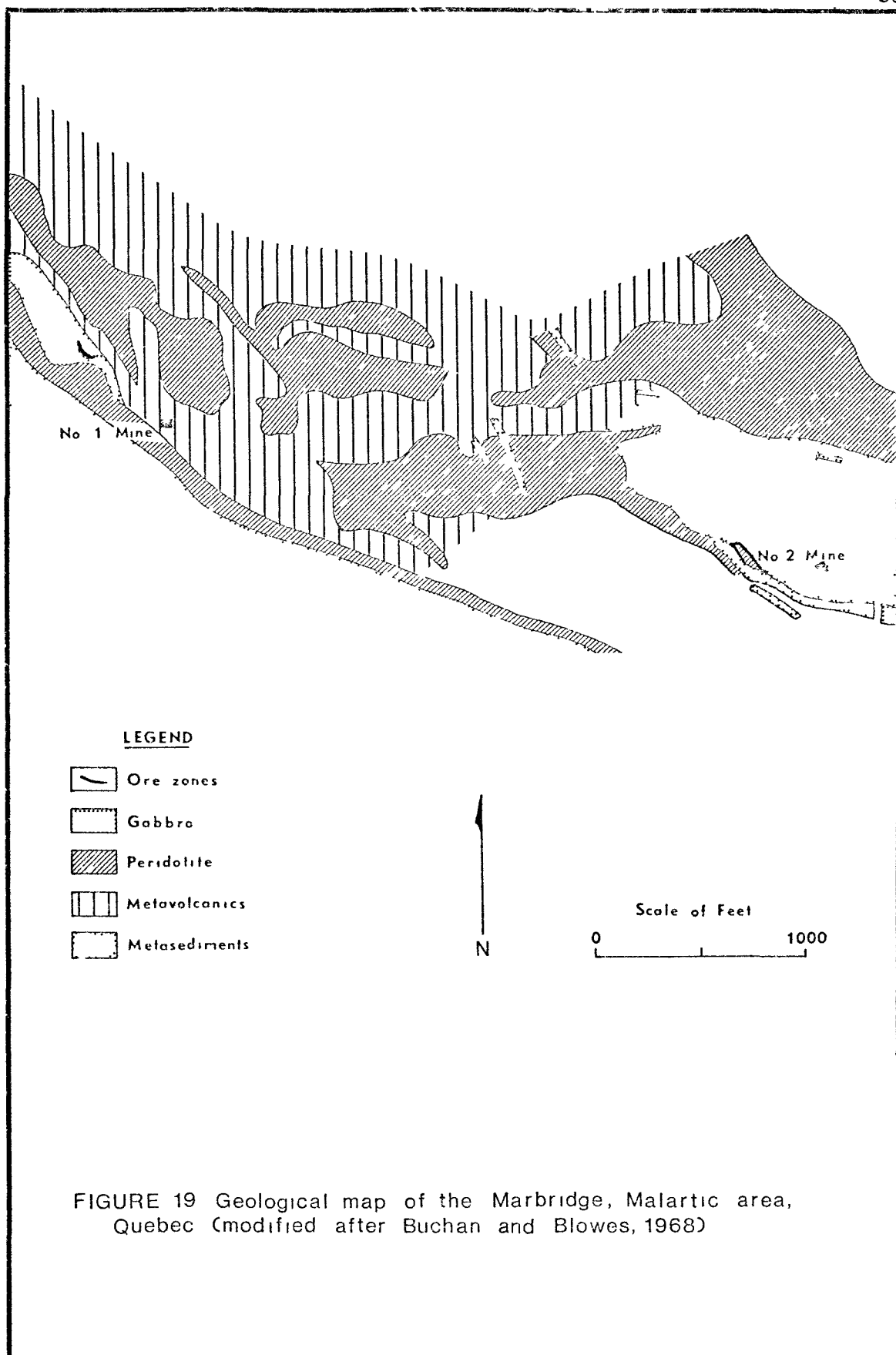subsequently mineralized. [29] Watson (1928) commented on the
apparent close association of these acidic dykes with the
known ore bodies, with the suggestion that the origin of such
dykes might have been the granitic batholith to the north, the
relative age of which was unconfirmed. [30] It is suggested that
part of this granite may have been emplaced prior to the in-
trusion of the peridotite with the acidic dykes occurring after
the gabbro intrusions but prior to the emplacement of the sul-
phide mineralization. Limited drilling prior to 1928 indicated
that massive sulphide bands cut the peridotite lenses, with
disseminated sulphides found to be contained within a major
portion of the peridotite. [31]

The Marbridge, Malartic Area

Within the area of the Marbridge No. 1 and No. 2 mines
(Figure 19), the oldest formations are composed of acidic and
basic volcanic tuff. Sediments were apparently later deposited
with both the sedimentary and volcanic formations being
subsequently highly folded and intruded by irregular, elongate
masses of peridotite and pyroxenite, considered by Buchan
and Blowes (1968) to have been products of differentiation from
a common magma. [32] These ultrabasic intrusions were intruded
by gabbro dykes which were in turn brecciated by narrow acidic
dykes of feldspar porphyry. [33] Dykes of hornblende syenite
were noted to occur at both mines, however, their age relation-
ship with the other intrusive formations was not defined. A
possibility exists that such acidic dykes may have intervened
between the intrusions of the peridotite masses and the later
gabbro dykes. All of the intrusive rocks, with the exception of
the hornblende syenite dykes, were noted to be cut by sulphide

LEGEND

[⌐] Ore zones

[   ] Gabbro

[▨▨▨] Peridotite

[||||] Metavolcanics

[   ] Metasediments

N

Scale of Feet

0   1000

FIGURE 19 Geological map of the Marbridge, Malartic area,
Quebec (modified after Buchan and Blowes, 1968)

mineralization. [34] The extensive alteration of the basic in-
trusives may be a partial product of hydrothermal solutions from
depth or from the later intrusion of granites which virtually
isolated the Marbridge area.

At the No. 1 mine, mineralization was apparently emplaced
as two separate phases, as interpreted by Clarke (1965).[35]
The initial emplacement of approximately 30 per cent dissemin-
ated sulphides was contained within a fine-grained mass of
peridotite which was in turn sheared and forcefully injected by
massive sulphides. The belief was expressed that the two in-
trusions of sulphides and also those of peridotite and gabbro
were "products of the same differentiation process." [36]

At the No. 2 mine, approximately 60 per cent of the ore
was composed of millerite, with a content of approximately 65
per cent nickel as compared with the usual nickel sulphide
mineral pentlandite which contains approximately 35 per cent
nickel. Samples of pentlandite at this mine were also noted
to contain a greater than average content of nickel, namely
42.6 per cent. Buchan and Blowes (1968) postulated that such
nickel-rich sulphides were formed by an interaction between
the pre-existing ultrabasic masses and the later, extensive
intrusions of granites. [38] The suggestion might be made
that such nickel-rich assemblages were products of different-
iation at depth with intrusion into place as a later phase than
the usual pyrrhotite and pentlandite assemblage present at the
No. 1 mine, but earlier than the minor intrusions containing
sphalerite which were noted to occur at both mines.

Table 8
SUMMARY OF SEQUENCES OF EVENTS

Lynn Lake Area	Moak Lake-Setting Lake Area	Bird River Area	Werner Lake-Gordon Lake Area	Shebandowan Area	Marbridge, Malartic Area
minor flows of rhyolite and trachyite followed by major extrusions of andesite tuff and breccia	extrusions of andesite and/or basalt flows	andesite and basalt flows	(volcanics not exposed in the immediate area)	extrusions of rhyolite and trachyite followed by basalt, andesite and dacite	extrusions of acidic and basic tuffs
---------------	---------------	period of erosion	and deposition --	---------------	---------
---------------	---------------	period of major folding	--	---------------	---------
granite	granite	granite	granite	(?)	(?)
	(?) basic sills				
	(?) granite				
diorite, gabbro and norite	peridotite and minor dunite and pyroxenite	peridotite and gabbro	peridotite and pyroxenite	peridotite	peridotite and pyroxenite
(?) granitic dykes					(?)hornblende syenite dykes
peridotite	(?)peridotite	gabbro	(?)'amphibolite'	gabbro	gabbro
quartz hornblende diorite					(?)peridotite & diss. sulph.
---------	---------------	------ brecciation	---------------	---------------	-----
granitic dykes, pegmatite and feldspar porphyry	pegmatite dykes	felsite	granite-pegmatites	porphyritic quartz and feldspar dykes	feldspar porphyry dykes
---------	------------	massive sulphide	mineralization --	---------------	-----

FOOTNOTES FOR CHAPTER IV

1 J.D. Allan, 1950, "The Lynn Lake Nickel Area, Manitoba,"
Transactions of the Canadian Institute of Mining and Metallurgy,
vol. 53, p. 344.

2 G.D. Ruttan, 1955, "Geology of Lynn Lake," Transactions of
the Canadian Institute of Mining and Metallurgy, vol. 58, p. 193.

3 R.F. Emslie and J.M. Moore, Jr., 1961, Geological Studies
of the Area between Lynn Lake and Fraser Lake, Department
of Mines and Natural Resources, publ. 59-4, pp. 48-52.

4 G.C. Milligan, 1960, Geology of the Lynn Lake District,
Department of Mines and Natural Resources, Manitoba, publ. 57-1,
pp. 177-78.

5 Ibid., pp. 178-79.

6 Allen, 1950, op. cit., p. 345.

7 Ruttan, 1955, op. cit., p. 197.

8 Ruttan, 1955, loc. cit.

9 J.F. Davies, B.B. Bannatyne, G.S. Barry and H.R. McCabe,
1962, Geology and Mineral Resources of Manitoba, Winnipeg,
Department of Mines and Natural Resources, Manitoba, p. 104.

10 H.F. Zurbrigg, 1963, "Thompson Mine Geology," Transactions
of the Canadian Institute of Mining and Metallurgy, vol. 66, p. 228.

11 J.M. Patterson, 1963, Geology of the Thompson-Moak Lake Area,
Winnipeg, Department of Mines and Natural Resources, Manitoba,
publ. 60-4, p. 21.

12 Zurbrigg, 1963, loc. cit.

13 C.J.A. Coats, 1968, "Serpentine Minerals from Manitoba,"
Canadian Mineralogist, vol, 9, pt. 3, p. 322.

14 Davies et al, 1962, op. cit., p. 110.

15 Ibid., p. 109.

16 Coats, 1968, loc. cit.

17 J.F. Davies, 1955, Geology and Mineral Deposits of the
Bird Lake Area, Winnipeg, Department of Mines and Natural
Resources, Manitoba, publ. 54-1, pp. 18-20.

18 H.C. Cooke, 1921, "Geology and Mineral Resources of
Rice Lake and Oiseau River Areas, Manitoba," Geological Survey,
Canada, Sum. Rept., pt. C. p. 12C.

19 Davies et al, 1962, op. cit., p. 37.

20 Davies, 1955, op. cit., p. 15.

21 Ibid., p. 28.

22 H.D. Carlson, 1958, "Geology of the Werner Lake-Rex Lake
Area," Department of Mines, Ontario, Annual Report, vol. 66,
pt. 4, pp. 15-16.

23 Ibid., pp. 12-15.

24 Carlson, 1958, op. cit., p. 12.
    E.R. Rose, 1958, Gordon Lake Nickel Deposit, Ontario,
Geological Survey, Canada, paper 58-6, p. 5.

25 Carlson, 1958, op. cit., p. 24.
    Rose, 1958, op. cit., pp. 4-5.

26 R.J. Watson, 1929, "Platinum-Bearing Nickel-Copper Deposit
on Lower Shebandowan Lake, District of Thunder Bay,"
Department of Mines, Ontario, Annual Report, vol. 37, pt. 4, pp.131-32.

27 Ibid., p. 131.
    D.H. Watkinson and T.N. Irvine, 1964, "Peridotitic Intrusions
near Quetico and Shebandowan, Northwestern Ontario: A Contribution
to the Petrology and Geochemistry of Ultramafic Rocks,"
Canadian Journal of Earth Sciences, vol. 1, p. 75.

28 Ibid., p. 75.

29 Watson, 1929, op. cit., p. 134.

30 Watson, 1929, op. cit., p. 148.

31 Watson, 1929, op. cit., pp. 146-47.

32 R. Buchan and J.H. Blowes, 1968, "Geology and Mineralogy
of a Millerite Nickel Ore Deposit, Marbridge No. 2 Mine,
Malartic, Quebec," Bulletin of the Canadian Institute of Mining
and Metallurgy, vol. 61, no. 672, p. 531.

33 Ibid., p. 531.

34 Ibid., pp. 531-32.

35 L.A. Clark, 1965, Geology and Geothermetry of the
Marbridge Nickel Deposit, Malartic, Quebec," _Economic Geology_,
vol. 60, pt. 1, pp. 799-802.

36 _Ibid_., p. 810.

37 Buchan and Blowes, 1968, _op. cit_., p. 532.

38 Buchan and Blowes, 1968, _op. cit_., p. 534.

66

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Summation of the Apparent Sequences of Events

As expressed by Table 4, (see pages 15 and 16), the sequence
of intrusive events in the Sudbury area is basically grouped into
five periods, with each period distinguished by an acidic
intrusion followed by one or more basic intrusions. A genetic
relationship has been shown to exist throughout the sequence
of intrusive events by the presence of a characteristic inter-
growth of quartz and feldspar (see page 36). Such periodic and
genetic relationships are indicative of a basic magma at depth
which underwent differentiation with periodic expulsions of
acidic and basic fractions. With this line of reasoning, a
new diagrammatic concept of the Sudbury irruptive has been
suggested as an explanation for the presently exposed surface
features expressed by the irruptive and the surrounding
country rocks (Figure 6). The genesis of the numerous and
productive ore deposits has been viewed as an integral part of
magmatic differentiation at depth. With reference to Tables 4
and 7 (pages 15,16and 43), the closing events of periods
(4), (5), and (6) apparently carried increasingly significant
amounts of sulphide mineralization. In each case the immediately
preceding, intrusive formation was composed of a basic composition,
having been preceded by an intrusive of acidic composition.
Such relationships appear indicative that the nickel sulphides were
an integral part of a basic magma at depth. During a slow process

of differentiation by crystal-formation and gravitational settling,
the disseminated sulphides gradually accumulated in the lower
portion of the remaining fluid magma and consequently were
associated in the magma reservoir with the deeper fractions
of basic composition to a greater extent than with the upper
fractions of acidic composition.

The sequences of apparent events in the Lynn Lake, Moak Lake-
Setting Lake, Bird River, Werner Lake-Gordon Lake, Shebandowan
and Marbridge, Malartic areas also appear to be indicative of
a process of magmatic differentiation at depth. With the
exception of the Werner Lake-Gordon Lake area where only meta-
sediments are exposed, there is evidence in all of the areas
that the initially extruded, volcanic lavas and pyroclastics
were of a more acidic composition than the extrusions which followed.
Following the volcanic activity, each area underwent a lengthy
period of sedimentation and a period of major folding. In the
Lynn Lake, Moak Lake-Setting Lake, Bird River, and Werner Lake-
Gordon Lake areas, the observed evidence indicates that granite
was intruded toward the end of the period of folding. Granitic
intrusives may also have been emplaced at such relative time
in the Shebandowan and Marbridge, Malartic areas, however, late
intrusions of granite have masked evidence of possible, earlier,
granitic intrusives. Intrusions of basic and ultrabasic
composition were in turn emplaced in all of the areas, with
suggested degrees of partial differentiation in place of these
intrusives in the Lynn Lake, Bird River, Werner Lake-Gordon
Lake and Marbridge, Malartic areas. Later minor intrusions of
peridotite were inferred possibilities in the Lynn Lake and
Moak Lake-Setting Lake areas, with probable, later intrusions
of gabbro in the Bird River, Werner Lake-Gordon Lake and
Shebandowan areas, and with decidedly later intrusions of gabbro
in the Marbridge, Malartic area. In all areas, minor dykes of
acidic composition intervened between the afore-mentioned, major

basic and ultrabasic intrusions and the emplacement of massive
nickel sulphide mineralization.

Bearing of Study on Hypotheses of Ore Emplacement

The hypothesis of magmatic segregation in place, which
envisions the settling of immiscible sulphide droplets from a
basic mass, can not be considered as a feasible manner of
nickel concentration if one or more intervening intrusions have
occurred between the emplacement of a basic mass and massive
nickel sulphides. As stated above, one or more intervening
intrusions have been noted in each area.

The hypothesis that nickel mineralization was emplaced by
hydrothermal solutions may also be considered to be unfeasible.
Despite the occurrence of hydrothermal alteration within the
relative areas of the nickel deposits at Sudbury, Lynn Lake and
Moak Lake-Setting Lake, there is not a close, spatial association
of hydrothermal alteration with the massive sulphide deposits.
This statement is borne out by the occurrences of unaltered,
basic inclusions in the midst of massive nickel sulphides in the
Sudbury, Lynn Lake and Moak Lake-Setting Lake areas. [1]

The possibility that all of the ores in the Sudbury area
were introduced along with intrusions of quartz diorite may also
be considered as an unfeasible hypothesis. As noted by Table 7
(page 43), the quartz diorite may have contained approximately
0.3 per cent nickel upon emplacement, or part of this percentage
might have been added during the later period of brecciation
and mineralization. The fact that three intrusives intervened
between the emplacement of the quartz diorite and the massive
nickel sulphides casts considerable doubt on the hypothesis that
the sulphides within the quartz diorite settled out and were
subsequently re-mobilized by brecciation and hydrothermal
solutions into apparently open fissures to form massive
sulphide deposits.

From the evidence presented, the only hypothesis which can
reasonably account for the igneous activity and the genesis
of the concentrated nickel sulphide mineralization in all of the
reviewed areas is the hypothesis of magmatic differentiation at
depth as originally hypothesized by Howe (1914), [2] later modified
by Bateman (1917) [3] and extended by the writer.

Spatial Relationships of the Nickel Ore Deposits

As shown by Figure 4, the ore deposits of the Sudbury
area are spatially related to the periphery of the irruptive
and to the offsets. Such a close relationship with the
irruptive may be explained with reference to the hypothetical
cross-sections (Figures 5 and 6). The initial tension fractures,
shown in such figures, are considered by the writer to be zones:
(a) along which the volcanic tuff was extruded (event 2a and b)
and extensive brecciation occurred;
(b) along which the irruptive was emplaced (events 3a & 3b);
(c) and along which all of the later intrusions of differentiated
magma were injected, including the three injections of sulphide
mineralization (events 4c, 5c and 6c).

Bands of brecciation, shown by Figure 8 to roughly parallel
the southern contact of the irruptive, have been considered by
Phemister (1956) and Speers (1957) to occur in tension fractures
or fissures as indicated by an apparent lack of displacement of the
adjacent country rocks. [4] Such brecciated zones along tension
fractures are considered by the writer to be representative of
the hypothesized, initial tension fractures mentioned above.
Periodic accumulations of pressure in the magma reservoir are
considered to have re-activated the tension fracture zones along
the outer contact of the irruptive and released the accumulations
of pressure by injections of differentiated magmas and sulphides
along such zones.

In the Lynn Lake area (Figure 12), the basic, plug-like bodies

are roughly aligned in a north-northeast direction, as are the
major faults and orebodies. Such a spatial relationship of
features implies a genetic association and the possible existence
of zones of tension fractures or faults at depth along which
were injected the basic, plug-like bodies, the minor acidic,
basic and ultrabasic intrusives and the ore mineralization.

In the Moak Lake-Setting Lake area (Figure 15), the north-
northeastward trend of the acidic and ultrabasic intrusions,
and the orebodies suggests emplacement along tension fractures
or fault zones. In all of the remaining areas, the ore zones
and the lens or plug-like bodies of basic and ultrabasic
composition exhibit linear trends suggestive of emplacement
along common zones of tension fractures or faults.
(Figures 16, 17, 18 and 19).

Generalizations of Occurrence, Structure and Genesis

With reference to the consideration of the Sudbury deposits
as "unique in their occurrence, structure and genesis", [5]
the following generalizations might be made concerning the seven
areas studied.

Occurrence

(a) The nickel deposits occur in areas of highly folded and
metamorphosed volcanic and sedimentary formations. Such areas
may represent former mountain ranges which have been uplifted
and subsequently eroded.

(b) In all areas, the nickel deposits occur in spatial
association primarily with basic and ultrabasic intrusions
and to a less apparent degree with acidic intrusions.

Structure

(a) The various deposits appear to be spatially associated
with zones of tension fractures which may or may not have
become fault zones by later differential movement. All of the
orebodies have been noted to show linear trends suggestive of
intrusion along zones of tension fractures.

(b) Brecciation of rock formations adjacent to such zones appears to have been a common occurrence prior to emplacement of sulphide mineralization.

Genesis

(a) Each deposit is primarily composed of a characteristic assemblage of the sulphide minerals pyrrhotite $Fe_{1-x}S$, pentlandite $(Fe,Ni)S$, and chalcopyrite $CuFeS_2$.

(b) The sequences and spatial associations of igneous formations in the seven areas are suggestive of the probability that the sulphide deposits have originated from basic magmas at depth, with a concentration of the contained sulphides by a common process of magmatic differentiation, and with periodic ejections of concentrated, sulphide fractions to form the various nickel ore deposits.

Such generalizations may prove relevant to future exploration, assessment and development of potential, nickel resource-areas within the Canadian Shield.

Recommendations for Future Development

With regard to the presently developed areas, a recommendation might be made for further exploration of possible tension fracture zones which may or may not be distinguished by brecciation. In the Sudbury area, the southwestern extension of the Frood breccia zone, as shown in Figure 9, might prove worthy of further exploration at depth. The Laurie River fault zone and associated basic plugs in the Lynn Lake area (Figure 12) may merit further exploration. In the Moak Lake-Setting Lake area (Figure 15), the spatial association of granite bodies with known ore deposits is suggestive that additional deposits might be expected in the respective, surrounding areas. In the Bird River area (Figure 16), a narrow band of gabbroic rock, noted by Davies (1955) to occur along the north shore of Bernic Lake, might prove to be indicative of a sill-like body underlying Bernic Lake on the southern limb of the apparent synclinal structure. [6]

FOOTNOTES FOR CHAPTER V

1 G.D. Ruttan, 1955, "Geology of Lynn Lake," <u>Transactions</u>
<u>of the Canadian Institute of Mining and Metallurgy</u>, vol. 58,
pp. 194-95.
    personal observation in the Sudbury and Thompson areas.

2 E. Howe, 1914, "Petrographical Notes on the Sudbury Nickel
Deposits," <u>Economic Geology</u>, vol. 9, no. 6, pp. 521-22.

3 A.M. Bateman, 1917, "Magmatic Ore Deposits, Sudbury,
Ontario, " <u>Economic Geology</u>, vol. 12, no. 5, p. 418.

4 T.C. Phemister, 1925, "Igneous Rocks of Sudbury and their
Relation to the Ore Deposits," <u>Department of Mines, Ontario</u>,
vol. 34, pt. 8, 1926, p. 96.
    E.C. Speers, 1957, "The Age Relation and Origin of Common
Sudbury Breccia," <u>Journal of Geology</u>, vol. 65, p. 504.

5 A.B. Yates, 1948, "Properties of the International Nickel
Company of Canada" in <u>Structural Geology of Canadian Ore Deposits</u>,
Jubilee Volume, Montreal, Canadian Institute of Mining and
Metallurgy, p. 596.

6 J.F. Davies, 1955, <u>Geology and Mineral Deposits of the</u>
<u>Bird Lake Area</u>, Winnipeg, Department of Mines and Natural
Resources, Manitoba, publ. 54-1, p. 16.

BIBLIOGRAPHY

Allan, J.D., 1950. "The Lynn Lake Area, Manitoba." Canadian
    Institute of Mining and Metallurgy, Transactions. vol. 53,
    pp. 343-48.

Bateman, A.M., 1917. "Magmatic Ore Deposits, Sudbury, Ontario."
    Economic Geology. Vol. 12, no. 5, pp. 391-426.

Bateman, A.M., 1951. The Formation of Mineral Deposits. New
    York: John Wiley and Sons.

Bell, R., 1890. "Report on the Sudbury Mining District."
    Geological Survey, Canada. vol. 5, pt. F.

Billings, M.P., 1954. Structural Geology. New Jersey:
    Prentice-Hall.

Buchan, R. and Blowes, J.H., 1968. "Geology and Mineralogy
    of a Millerite Nickel Ore Deposit, Marbridge No. 2 Mine,
    Malartic, Quebec." Canadian Institute of Mining and
    Metallurgy, Bulletin. vol. 61, no. 672, pp. 529-35.

Burrows, A.G. and Rickaby, H.C., 1934. "Sudbury Nickel Field
    Restudied." Department of Mines, Ontario. vol. 43, pt. 2,
    pp. 1-45.

Carlson, H.D., 1958. "Geology of the Werner Lake-Rex Lake Area."
    Department of Mines, Ontario. vol. 66, pt. 4, pp. 1-27.

Clark, L.A., 1965. "Geology and Geothermetry of the Marbridge
    Nickel Deposit, Malartic, Quebec." Economic Geology.
    vol. 60, pt. 1, pp. 792-811.

Clarke, A.M. and Potapoff, P., 1959. "Geology of McKim Mine."
    Geological Association of Canada, Proceedings. vol. 11,
    pp. 67-80

Coats, C.J.A., 1968. "Serpentine Minerals from Manitoba."
    Canadian Mineralogist. vol. 9, pt. 3, pp. 322-47.

Coleman, A.P., 1903. "The Sudbury Nickel Deposits."
    Ontario Bureau of Mines. rept. no. 12, pp. 235-303.

Collins, J.H., 1888. "The Sudbury Copper Deposits." Quarterly
    Journal of the Geological Society, London. vol. 44,
    pp. 834-38.

Collins, W.H., 1934. "Life History of the Sudbury Nickel
    Irruptive." Royal Society of Canada, Transactions.
    vol. 28, sect. 4, pp. 123-177.

Collins, W.H., 1935. "The Life History of the Sudbury Nickel
    Irruptive. II. Shape." Royal Society of Canada, Transactions.
    vol. 29, sect. 4, pp. 27-47.

Cooke, H.C., 1921. "Geology and Mineral Resources of Rice Lake
    and Oiseau River Areas, Manitoba." Geological Survey, Canada.
    Summary Report, pt. C, pp. 1-36.

Cooke, H.C., 1946. Problems of Sudbury Geology. Geological Survey,
    Canada. bull. no. 3, pp. 1-77.

Cowan, J.C., 1967. "Geology of the Strathcona Ore Deposit."
    Canadian Mining and Metallurgical Bulletin. vol. 1, no. 669,
    1968, pp. 38-54.

Davies, J.F., 1955. Geology and Mineral Deposits of the Bird
    Lake Area, Lac du Bonnet Mining Division, Manitoba.
    Department of Mines and Natural Resources, Manitoba. publ.
    54-1.

Davies, J.F., Bannatyne, B.B., Barry, G.S. and McCabe, H.R.,
    1962. Geology and Mineral Resources of Manitoba.
    Department of Mines and Natural Resources, Manitoba.

Dickson, C.W., 1903. "The Ore Deposits of Sudbury, Ontario."
    American Institute of Mining Engineering, Transactions.
    vol. 34, pp. 1-65.

Dietz, R.S., 1962. "Sudbury Structure as an Astrobleme."
    Journal of Geology. vol. 72, 1964, pp. 412-34.

Emslie, R.F. and Moore Jr., L.M., 1961. "Geological Studies
    of the Area between Lynn Lake and Fraser Lake."
    Department of Mines and Natural Resources, Manitoba.
    publ. 59-4.

Fairbairn, H.W., Hurley, P.M. and Pinson, W.H., 1960.
    "Mineral and Rock Ages at Sudbury-Blind River, Ontario."
    Geological Association of Canada, Proceedings.
    vol. 12, pp. 41-66.

Fairbairn, H.W. and Robson, G.M., 1942. "Breccia at
    Sudbury, Ontario." Journal of Geology. vol. 50, no. 1,
    pp. 1-33.

Ginn, R.M., 1958. A Study of the Granitic Rocks in the Sudbury
    Area. Unpublished M.S. Thesis. Queen's University,
    Kingston.

Harker, A., 1916. "Differentiation in Intercrustal Magma Basins." Journal of Geology. vol. 24, pp. 555-58.

Hawley, J.E., 1962. "The Sudbury Ores: Their Mineralogy and Origin. Canadian Mineralogist. vol. 7, pt. 1, pp. 1-207.

Howe, E., 1914. "Petrographical Notes on the Sudbury Nickel Deposits." Economic Geology. vol. 9, no. 6, pp. 505-22.

Killin, A.F., 1966. Nickel. Department of Mines and Resources, Canada. no. 37.

Knight, C.W., 1917. Report of the Royal Ontario Nickel Commission. Toronto, pp. 105-211.

Knight, C.W., 1923. "The Chemical Composition of the Norite -Micropegmatite, Sudbury, Ontario, Canada." Economic Geology, vol. 18, pp. 592-94.

Lochhead, D.R., 1955. "The Falconbridge Ore Deposit, Canada." Economic Geology. vol. 50, no. 1, pp. 42-50.

Milligan, G.C., 1960. Geology of the Lynn Lake District, Manitoba. Department of Mines and Natural Resources, Manitoba. publ. 57-1.

Mitchell, G.P. and Mutch, A.D., 1957. "Hardy Mine." in Structural Geology of Canadian Ore Deposits. Congress Volume, Montreal: Canadian Institute of Mining and Metallurgy. pp. 350-63.

Naldrett, A.J. and Kullerud, G., 1967. "A Study of the Strathcona Mine and Its Bearing on the Origin of the Nickel-Copper Ores of the Sudbury District, Ontario." Journal of Petrology. vol. 8, pt. 3, pp. 453-531.

Patterson, J.M., 1963. Geology of the Thompson-Moak Lake Area. Department of Mines and Natural Resources, Manitoba. publ. 60-4.

Robson, G.M., 1940. Sudbury Breccia. Unpublished M.A. Thesis. Queen's University, Kingston.

Rose, E.R., 1958. Gordon Lake Nickel Deposit, Ontario. Geological Survey, Canada. paper 58-6.

Ruttan, G.D., 1955. "Geology of Lynn Lake." Canadian Institute of Mining and Metallurgy. vol. 58, pp. 191-200.

Smith, C.H., 1961. "Ultramafic Intrusions in Canada and their Significance to Upper Mantle Studies." Canadian Geophysical Bulletin. vol. 14, pp. 157-69.

Sopher, S.R., 1963. Palaeomagnetic Study of the Sudbury Irruptive. Geological Survey, Canada. bull. 90.

Souch, B.E. and Members of the Geological Staff of the International Nickel Co. of Canada Ltd., 1966. "The Sulfide Ores of Sudbury: Their Particular Relation to a Distinctive Inclusion-Bearing Faces of the "Nickel Irruptive." (Abstract) Economic Geology. vol. 61, pt. 1, p. 801.

Souch, B.E., Podalsky T., and Geological Staff of the International Nickel Co. of Canada Ltd., 1967. "The Sulfide Ores of Sudbury: Their Particular Relation to a Distinctive Inclusion-Bearing Faces of the Nickel Irruptive." (Unpublished Study) Symposium on Magmatic Ore Deposits, Stanford University, California, Society of Economic Geologists.

Speers, E.C., 1956. The Age Relations and Origin of the Sudbury Breccia. Unpublished Ph.D. Thesis. Queen's University, Kingston.

Speers, E.C., 1957. "The Age Relation and Origin of Common Sudbury Breccia." Journal of Geology. vol. 65, pp. 497-514.

Stevenson, J.S., 1963. "The Upper Contact Phase of the Sudbury Micropegmatite." Canadian Mineralogist. vol. 7, pp. 413-19.

Thomson, J.E., 1956. Geology of Falconbridge Township." Department of Mines, Ontario. vol. 66, pt. 6, 1957, pp. 1-33.

Walker, T.L., 1897. "Geological and Petrographical Studies of the Sudbury Nickel District (Canada)." Quarterly Journal of the Geological Society, London. vol. 53, pp. 40-66.

Wandke, A. and Hoffman, R., 1924. "A Study of the Sudbury Ore Deposits." Economic Geology. vol. 19, pp. 169-204.