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

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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

The writer wishes to express his appreciation to his adviser Mr. J.A. Hall for his interest, encouragement, and many helpful suggestions; to the faculty of the department of geography for their consideration of this topic as being worthy of geographical study; to the department of geography for aid in assembling the final draft of the study; and to Mrs. L. Peirce for her typing of this study.
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 potential, 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 determining 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 initial 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 microscopic intergrowths of quartz and feldspar. Increasingly, significant 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 concept 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.
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CHAPTER I

SCOPE OF THE STUDY

Introduction

In terms of area, the Canadian Shield represents approximately half of the total land area of Canada, its largest physiographic 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 developed and potential resources of this area need to be fully evaluated for knowledgable development and management. It would appear significant that Sudbury, the area's second largest city, is virtually 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

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Classification of Rock Types</th>
<th>Nickel in%</th>
<th>Iron Oxides &amp; Magnesia in%</th>
<th>Silica &amp; Alumina in%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>acidic</td>
<td>0.0002</td>
<td>4.4</td>
<td>78.7</td>
</tr>
<tr>
<td>Diorite</td>
<td>intermediate</td>
<td>0.004</td>
<td>11.7</td>
<td>73.4</td>
</tr>
<tr>
<td>Gabbro</td>
<td>basic</td>
<td>0.016</td>
<td>16.6</td>
<td>66.1</td>
</tr>
<tr>
<td>Peridotite</td>
<td>ultrabasic</td>
<td>0.20</td>
<td>43.3</td>
<td>45.9</td>
</tr>
</tbody>
</table>


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 intrusion (Bell, 1890) (Naldrett and Kullerud, 1967).

(b) hydrothermal processes - leaching and concentration of sulphides from a basic body by reaction with heated solutions emanating from depth or from nearby intrusive bodies
(Dickson, 1904).

(c) magmatic differentiation at depth - gravitational segregation 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 occurrence 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


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. 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

<table>
<thead>
<tr>
<th>Company</th>
<th>INCO $^2$</th>
<th>FALCO $^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of operating mines</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Concentrating capacity in tons of ore per day</td>
<td>66,500</td>
<td>12,800</td>
</tr>
<tr>
<td>Number of tons mined in 1968</td>
<td>24,350,000 *</td>
<td>3,208,000</td>
</tr>
<tr>
<td>Total ore reserves as of December 31, 1968</td>
<td>370,970,000 *</td>
<td>91,638,600</td>
</tr>
</tbody>
</table>

* - 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

<table>
<thead>
<tr>
<th>Mining Company</th>
<th>Lynn Lake Area 4</th>
<th>Moak Lake-Setting Lake Area 5</th>
<th>Bird River Area 6</th>
<th>Werner Lake-Gordon Lake Area 7</th>
<th>Shebandowan Area 8</th>
</tr>
</thead>
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<tr>
<td>Commencing Year of Production</td>
<td>Sherritt Gordon Nickel Mines Ltd.</td>
<td>INCO</td>
<td>Consolidated Canadian Faraday Ltd.</td>
<td>Consolidated Canadian Faraday Ltd.</td>
<td>INCO (planned production in 1972)</td>
</tr>
<tr>
<td>Number of Producing Mines</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Concentrating Capacity in Tons per Day</td>
<td>4,000</td>
<td>15,000</td>
<td>700 (concentrated at Werner Lake Mill)</td>
<td>1,200 (including ore from Bird River Area)</td>
<td>2,900</td>
</tr>
<tr>
<td>Tonnage Mined in 1968</td>
<td>1,276,517</td>
<td>*</td>
<td>-</td>
<td>207,417</td>
<td>-</td>
</tr>
<tr>
<td>Total Ore Reserves in Tons as of December 31, 1968</td>
<td>12,600,000 @ 0.81% nickel &amp; 0.40% copper</td>
<td>*</td>
<td>1,350,000 @ 1.06% ni. &amp; 0.34% cu.</td>
<td>593,268 @ 1.10% ni. &amp; 0.52% cu.</td>
<td>(unavailable)</td>
</tr>
</tbody>
</table>

* - 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 published 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 relationship 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 emplaced 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 mineralization was concentrated by magmatic differentiation from the Sudbury irruptive, by differentiation in a magmatic 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 deposits 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 formations 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.
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 7. Diagrammatic cross section of the Sudbury irruptive. (after Wilson, 1956)

LEGEND

- Quartz diorite
- Granite
- Ultrabasic zone
- Norite
- Hybrid zone
- Micropegmatite
- Bedded volcanic tuff
- Volcanic tuff
- Quartzite breccia
- Gabbro
- Gneiss and granite
- Quartzite
- Greywacke, acidic and basic volcanic rocks


- Fault
- Major bands of breccia
- Dip of the outer contact of the Sudbury irruptive

- 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
has a basin-shape at depth. Consequently, this inferred structure has become commonly referred to as the Sudbury Basin. A basin-shape is similarly 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 micropegmatite (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 spatially related.

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

**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. 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 faulting were considered to dip inwards at angles of 30 to 90 degrees. 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).
(b) intrusion of the irruptive as a funnel-shaped body (Wilson, 1956).

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 hypothesis of intrusion around a downfaulted block carries the implication that a minimum amount of country rock would have to be displaced in order to accommodate 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 consideration modified and more extensive views of Knight's hypothesis 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).
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<th>Intrusion of the Irruptive</th>
<th>Post-irruptive Period</th>
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<td>(3a)</td>
<td>(4a)</td>
</tr>
<tr>
<td>intrusion of acidic composition, granite</td>
<td>intrusion of acidic composition, micropegmatite</td>
<td>intrusion of acidic composition, granite</td>
</tr>
<tr>
<td>(1b)</td>
<td>(3b)</td>
<td>(4b)</td>
</tr>
<tr>
<td>intrusion of basic composition, quartz gabbro</td>
<td>intrusion of basic composition, norite with very minor, disseminated mineralization</td>
<td>intrusion of basic composition, quartz diorite</td>
</tr>
<tr>
<td>(1c)</td>
<td></td>
<td>(4c)</td>
</tr>
<tr>
<td>intrusion of more basic composition, porphyritic olivine diabase</td>
<td></td>
<td>intrusion of more basic composition, quartz diorite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with inclusions of ultrabasic composition and disseminated mineralization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intrusion of acidic composition, aplite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intrusion of basic composition, trap rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5c)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>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</td>
</tr>
</tbody>
</table>
16

(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,\textsuperscript{14} the Sudbury area was uplifted, folded and faulted during a period of mountain-building.\textsuperscript{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.\textsuperscript{16}

A magma of basic composition is suggested as having welled up into the mountain core. With possible proportions of batholithic size and miles of overlying and insulating country rock, such a magma would be subject to a slow rate of cooling and crystallization, 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.\textsuperscript{17}

Events (la), (lb) and (lc)

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. 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. 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.

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. 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. Pulsations of pressure accompanying such violent extrusions 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 downfaulted block as basically two separate intrusions closely related 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 differentiation of the two fractions in place following the intrusion (see pages 38 and 39). At depth, the norite similarly underwent 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 subperiods, each consisting of an acidic intrusive event followed by one or more basic intrusive events.
<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>I Acid Offset Dyke</th>
<th>II Micropegmatite</th>
<th>III Complex</th>
<th>IV Volcanic Tuffs</th>
<th>V Norite</th>
<th>VI Quartz Diorite Offset Dykes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>71.45</td>
<td>67.83</td>
<td>63.14</td>
<td>65.9</td>
<td>55.16</td>
<td>58.55</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>12.17</td>
<td>13.36</td>
<td>14.65</td>
<td>11.6</td>
<td>16.86</td>
<td>15.75</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.03</td>
<td>1.28</td>
<td>1.52</td>
<td>1.7</td>
<td>1.94</td>
<td>2.16</td>
</tr>
<tr>
<td>FeO</td>
<td>4.18</td>
<td>4.39</td>
<td>5.17</td>
<td>4.9</td>
<td>6.50</td>
<td>6.41</td>
</tr>
<tr>
<td>CaO</td>
<td>1.35</td>
<td>2.04</td>
<td>4.03</td>
<td>2.7</td>
<td>7.42</td>
<td>6.15</td>
</tr>
<tr>
<td>MgO</td>
<td>0.94</td>
<td>1.50</td>
<td>2.85</td>
<td>3.6</td>
<td>5.17</td>
<td>4.07</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.06</td>
<td>3.39</td>
<td>3.20</td>
<td>3.5</td>
<td>2.87</td>
<td>2.63</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.49</td>
<td>3.82</td>
<td>2.91</td>
<td>2.9</td>
<td>1.35</td>
<td>2.07</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.06</td>
<td>1.21</td>
<td>1.24</td>
<td>1.8</td>
<td>1.28</td>
<td>1.06</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.79</td>
<td>0.68</td>
<td>0.74</td>
<td>0.4</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.66</td>
<td>0.21</td>
<td>0.23</td>
<td>0.1</td>
<td>0.25</td>
<td>0.27</td>
</tr>
<tr>
<td>S</td>
<td>0.08</td>
<td>0.05</td>
<td>0.08</td>
<td>0.12</td>
<td>0.23</td>
<td>-</td>
</tr>
<tr>
<td>MnO</td>
<td>0.13</td>
<td>0.07</td>
<td>0.08</td>
<td>0.2</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>CO₂</td>
<td>-</td>
<td>0.17</td>
<td>0.16</td>
<td>0.3</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>Total</td>
<td>100.39</td>
<td>100.00</td>
<td>100.00</td>
<td>99.6</td>
<td>100.00</td>
<td>100.23</td>
</tr>
</tbody>
</table>

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. 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 represents the Lady Violet granite, and a three-mile long body represents 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). Granites of such age have been also noted by Yates (1948) to occur along the northern range, however, their configurations were not fully mapped.

The age relationship between these granites and the irruptive has been the subject of considerable rationalization by some investigators in attempts to accommodate 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. 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. 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." Both dykes and small masses of granite, similar to the Murray type of granite, were
### Table 6

**CHEMICAL COMPOSITIONS OF GRANITES**

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Creighton Granite</th>
<th>Murray Granite</th>
<th>Lady Violet Granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>74.44</td>
<td>73.78</td>
<td>73.34</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>11.20</td>
<td>11.70</td>
<td>10.60</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.22</td>
<td>2.57</td>
<td>1.05</td>
</tr>
<tr>
<td>CaO</td>
<td>1.35</td>
<td>1.30</td>
<td>0.35</td>
</tr>
<tr>
<td>MgO</td>
<td>0.49</td>
<td>0.25</td>
<td>0.30</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.95</td>
<td>3.35</td>
<td>4.69</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.03</td>
<td>5.18</td>
<td>7.91</td>
</tr>
<tr>
<td>+H₂O</td>
<td>0.45</td>
<td>0.38</td>
<td>0.06</td>
</tr>
<tr>
<td>-H₂O</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>MnO</td>
<td>0.03</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.17</td>
<td>0.17</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>98.38</strong></td>
<td><strong>98.76</strong></td>
<td><strong>98.37</strong></td>
</tr>
</tbody>
</table>

noted to occur within the norite at distances of over two miles from the main masses of granite south of the irruptive. 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.

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. This more basic composition 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 offset dykes along apparent tension fractures which radiated outward 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 6, 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. (b) Near the Levack mine (Figure 6, 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.
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 intrusion 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 composition. 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 composition 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).
FIGURE 10. Cross-section of the Strathcona mine showing intrusive relationships of quartz diorites, breccias and ore zones (modified after Naldrett and Kullcrud, 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). 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. 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. 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. At the Falconbridge mine (southeast corner of the irruptive), the relationships between the faulting and the following brecciation are apparent (Figure 11). The initial faulting altered the adjacent wall rock to a chlorite
FIGURE 11 Cross-section and plan of part of the Falconbridge mine (southern range) showing relationships between faulting, hydrothermal alteration, brecciation and intrusion of sulphide ore (after Thomson, 1956)
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". 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).

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);
(b) noted to cut and include fragments of the Creighton and Murray granites;
(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;
(d) noted to cut the latest intrusion of quartz diorite at the Strathcona mine (northern range);
(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 plagioclase feldspar in the fragments to a more sodic composition, and added the secondary minerals of chlorite, epidote, biotite and quartz. A characteristic feature of such breccia was the presence of rounded 'eyes' or
porphyroblasts of quartz and feldspar. Despite the relatively close spatial association of breccia and ore zones, this metasomatic 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. There is evidence, however, that a significant portion of the disseminated mineralization 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)

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).

The intrusion of massive sulphide mineralization, which followed, apparently carried with it or was immediately preceded 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". Cowan (1967) also observed rims of hornblende and biotite around basic fragments at the Strathcona mine. 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 $\text{Fe}_{1-x}S$, pentlandite $(\text{Fe,Ni})S$, and chalcopryite $\text{CuFeS}_2$. 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


3 Ibid., pp. 141-43.

4 Ibid., p. 323.

5 Ibid., p. 182.

6 Ibid., p. 131.

7 Ibid., pp. 49 and 99.

8 Ibid., p. 182.


12 Knight, 1917, op. cit., p. 122.


16 Ibid., p. 9.


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.


Fairbairn and Robson, 1942, *loc. cit.*


A.M. Clarke and P. Potapoff, 1959, "Geology of McKim Mine,"


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

49 Yates, 1938, loc. cit.

50 Cowan, 1967, op. cit., p. 44.


52 Fairbairn and Robson, 1942, op. cit., p. 31.

    Speers, 1957, op. cit., p. 505.


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


60 Knight, 1917, op. cit., p. 155.

    Knight, 1917, loc. cit.

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 consequently 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
(3a) - micropegmatite
(3b) - norite
(4a) - Creighton granite
(4b) - quartz diorite
(4c) - an absence of micrographic intergrowth was noted in the fine-grained, second intrusion of quartz diorite
(6a) - pegmatite - noted along the eastern range to be intruded into brecciated rock adjacent to the irruptive and subsequently intruded by nickel sulphides

All of the above rock types are coarse-grained in texture, consequently there is the probability that micrographic intergrowth 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.

Nature of the Sudbury Irruptive

Concepts of the Irruptive

Basically the irruptive has been considered as being introduced into place as either:

(a) a single intrusion which differentiated in place into the component parts of micropegmatite and norite, as interpreted 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 concepts. At depth, a magma of basic composition may be considered as having differentiated into a basic fraction of noritic composition with an overlying, residual, acidic fraction of micropegmatitic composition. If a portion of such differentiated magma were expelled from the reservoir, the overlying micropegmatitic 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 composed 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". 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 significant 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. 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.

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 TiO₂, being representative of the heavy mineral ilmenite. 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. 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.

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).
Ultrabasic inclusions have been also noted within zones of massive sulphide mineralization. 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. 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."
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. Such inferred 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 Sulphur


<table>
<thead>
<tr>
<th>Mean values in ppm</th>
<th>Ni</th>
<th>Cu</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>micropegmatite</td>
<td>20</td>
<td>28</td>
<td>475</td>
</tr>
<tr>
<td>upper norite</td>
<td>35</td>
<td>40</td>
<td>950</td>
</tr>
<tr>
<td>norite (northern range)</td>
<td>60</td>
<td>55</td>
<td>950</td>
</tr>
<tr>
<td>norite (southern range)</td>
<td>75</td>
<td>50</td>
<td>1,100</td>
</tr>
<tr>
<td>discontinuous marginal facies</td>
<td>3,000</td>
<td>2,700</td>
<td>18,000</td>
</tr>
</tbody>
</table>

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


8 Ibid., p. 58.

9 Stevenson, 1963, loc. cit.


13 Ibid., p. 149.
15 Collins, 1934, op. cit., p. 175.
18 Yates, 1938, loc. cit.
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. Minor periods of sedimentation intervened between the explosions 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.
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 hydrothermal solutions which altered parts of the diorite, gabbro and norite to amphibolite, characterized by actinolitic hornblende. 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. 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. 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.
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.
LEGEND

- Diabase, Gabbro
- Granite
- Peridotite
- Metasediments, Volcanics, Schists
- Schists and Undifferentiated Metasediments
- Anticline Plunging
- Anticline Overturned
- Syncline Plunging
- Geological Boundary
- Local Trends
- Mine Shaft
- Nickel Occurrence

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-appearing, 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 composition 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. In an earlier study, Cooke (1921) considered this basic sill to have been intruded into the granite. 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. 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. Minor intrusions of felsite, quartz and carbonate followed the basic intrusions and were in turn fractured and mineralized by cross-cutting sulphide stringers. 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.
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. 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 hornblende in some locations. All of the basic and ultrabasic rock types were noted to be cut by later granite-pegmatites. 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.

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. Following a period of erosion, sedimentation, folding and faulting, lens-shaped bodies of peridotite were emplaced parallel with the regional foliation. These bodies were subsequently largely altered to
FIGURE 18 Geological map of the Shebandowan area, Ontario (modified after Watkinson and Irvine, 1964)
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. These ultrabasic intrusions were intruded by gabbro dykes which were in turn brecciated by narrow acidic dykes of feldspar porphyry. Dykes of hornblende syenite were noted to occur at both mines, however, their age relationship 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
FIGURE 19 Geological map of the Marbridge, Malartic area, Quebec (modified after Buchan and Blowes, 1968)
mineralization. The extensive alteration of the basic intrusives 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). The initial emplacement of approximately 30 per cent disseminated 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 intrusions 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 differentiation 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**

<table>
<thead>
<tr>
<th>Lynn Lake Area</th>
<th>Moak Lake-Setting Lake Area</th>
<th>Bird River Area</th>
<th>Werner Lake-Gordon Lake Area</th>
<th>Shebandowan Area</th>
<th>Marbridge, Malartic Area</th>
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</thead>
<tbody>
<tr>
<td>minor flows of rhyolite and trachyite followed by major extrusions of andesite tuff and breccia</td>
<td>extrusions of andesite and/or basalt flows</td>
<td>andesite and basalt flows</td>
<td>(volcanics not exposed in the immediate area)</td>
<td>extrusions of rhyolite and trachyite followed by basalt, andesite and dacite</td>
<td>extrusions of acidic and basic tuffs</td>
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<td>granite</td>
<td>granite</td>
<td>granite</td>
<td>(?)</td>
<td>(?)</td>
<td>(?)</td>
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<tr>
<td>(?) basic sills</td>
<td>(?) granite</td>
<td>(?) granite</td>
<td>(?) granite</td>
<td>(?) granite</td>
<td>(?)</td>
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<tr>
<td>diorite, gabbro and norite</td>
<td>peridotite and minor dunite and pyroxenite</td>
<td>peridotite and gabbro</td>
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<td>peridotite and pyroxenite</td>
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<td>(?) granitic dykes</td>
<td>(?) peridotite</td>
<td>gabbro</td>
<td>(?) 'amphibolite'</td>
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<td>quartz hornblende diorite</td>
<td></td>
<td></td>
<td></td>
<td>(?) peridotite</td>
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<td>&amp; diss. sulph.</td>
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<td>granitic dykes, pegmatite and feldspar porphyry</td>
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<td>granite-pegmatites</td>
<td>porphyritic quartz and feldspar dykes</td>
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<td></td>
<td></td>
<td>massive sulphide mineralization</td>
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</table>
FOOTNOTES FOR CHAPTER IV


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.


8 Ruttan, 1955, loc. cit.


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.


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.


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

21 Ibid., p. 28.


23 Ibid., pp. 12-15.


Rose, 1958, op. cit., pp. 4-5.


27 Ibid., p. 131.


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.


33 Ibid., p. 531.

34 Ibid., pp. 531-32.

36 Ibid., p. 810.

37 Buchan and Blowes, 1968, op. cit., p. 532.

38 Buchan and Blowes, 1968, op. cit., p. 534.
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 35). 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, 16 and 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 metasediments 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), later modified by Bateman (1917) 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. 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", 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 $\text{Fe}_{1-x}\text{S}$, pentlandite $(\text{Fe},\text{Ni})\text{S}$, and chalcopyrite $\text{CuFeS}_2$.

(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.
FOOTNOTES FOR CHAPTER V

   personal observation in the Sudbury and Thompson areas.


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